NOT TO BE CITED WITHOUT PRIOR
REFERENCE TO THE AUTHOR(S)

Northwest Atlantic Fisheries Organization

Serial No. N6816 **NAFO SCR Doc. 18/030**

SCIENTIFIC COUNCIL MEETING – APRIL 2018

Bayesian SCAA model for the 3M cod

by

Diana González-Troncoso[1], Carmen Fernández[2] and Fernando González-Costas[1]

[1]Instituto Español de Oceanografía, Vigo, Spain
[2]Instituto Español de Oceanografía, Gijón, Spain

Abstract

Different runs of a Bayesian SCAA model were conducted for the 3M cod during the benchmark of this stock, that took place in April 2018. The data inputs used in the last approved assessment in June 2017 were reviewed for the benchmark, resulting in some revisions; the revised data are used in this work. A comparison of the results of the scenarios with those from the last approved assessment (from June 2017) is performed. The Bayesian SCAA model is explored under different model settings and results show differences, which can be considerable, when the model settings are changed; this complicates the task of arriving to a final model configuration. The benchmark *recommended a Bayesian SCAA with structure similar to run 37 to form the basis of the assessment for this stock in June 2018, pending the sensitivity analyses described below: prior median of recruitment of 45000, CV on prior for recruitment and abundance at age in the first year as 10, including a full set of diagnostics.* The run that follows the recommendation of the benchmark is R42 from this document. The estimated SSB in 2016 from R42 is 3.5 times the SSB estimated in the last approved assessment.

Introduction

The 3M cod stock had been on fishing moratorium from 1999 to 2009 following its collapse, which has been attributed to three simultaneous circumstances: a stock decline due to overfishing, an increase in catchability at low abundance levels and a series of very poor recruitments starting in 1993. The assessments performed since the collapse of the stock confirmed the poor situation, with SSB at very low levels, well below B_{lim} (Vázquez and Cerviño, 2005). Nevertheless, recruitment was estimated above the historical average in 2005 and 2006 which in turn caused an increase of SSB that allowed the reopening of the fishery in 2009. Recruitment estimates from 2010 to 2012 (2009-2011 year-classes) had been the highest since 1992 (González-Troncoso, 2017).

A VPA based assessment of the cod stock in Flemish Cap was approved by NAFO Scientific Council (SC) in 1999 for the first time and was annually updated until 2002. However, catches between 2002 and 2005 were very small undermining the VPA based assessment, as its results are quite sensitive to assumed natural mortality when catches are at low levels. Cerviño and Vázquez (2003) developed a method which combines survey abundance indices at age with catchability at age, the latter estimated from the last reliable accepted XSA. The method estimates abundances at age with their associated uncertainty and allows calculating the SSB distribution and, hence, the probability that SSB is above or below any reference value. The method was used to assess the stock from 2003 until 2007. In 2007 results from an alternative Bayesian model were also presented (Fernández *et al.*, 2007) and in 2008 this Bayesian model was further developed and approved by the NAFO SC (Fernández *et al.*, 2008), having been used since then in the assessment of this stock. This assessment model assumes a prior distribution over the survivors of the last year (all ages) and of the oldest age for all previous years, and reconstructs the population going backwards over time and ages. For the years without catch-at-age data, a prior over the F-at-age is assumed in order to reconstruct the population in those years. The last approved assessment was based on this model and was performed during the June SC meeting 2017 (González-Troncoso, 2017).

During its meeting of September 2016, the NAFO Fisheries Commission expressed some concern that, in the 3M cod advice, the risk associated with F exceeding F_{lim} under the $F_{bar} = F_{lim}$ scenario might be underestimated. In this regard, a benchmark review of this stock assessment was requested. The results of the benchmark review will be considered in setting the TAC for 2019 in light of the new stock assessment in 2018. Moreover, during the 2017 NAFO Scientific Council meeting, some doubts about the appropriateness of some of the prior settings applied in the assessment were raised. Preliminary analysis showed that changing some of the settings changed the results of the assessment. Thus, the SC recommended to study more in depth the Bayesian XSA model and to explore alternative models to perform the assessment of this stock, and it was agreed that the best forum to do that would be the benchmark.

In this study, a Bayesian Statistical-Catch-At-Age (SCAA) is applied to explore its potential for the assessment of this stock.

Different scenarios (37) of this model were run during the 3M cod benchmark that took place in April 2018. Looking at the results, the NAFO SC concluded at the benchmark that (NAFO, 2018a): *SC recommended a Bayesian SCAA with structure similar to run 37 to form the basis of the assessment for this stock in June 2018, pending the sensitivity analyses described below: prior median of recruitment of 45000, CV on prior for recruitment and abundance at age in the first year as 10, including a full set of diagnostics.*

Following the recommendation of the SC, 7 more runs of the Bayesian SCAA were conducted. The results of all the runs are presented in this SCR.

Material and Methods

Data used

The data used in the last approved assessment was revised and updated during a SC meeting held by WebEx in March 2018 (NAFO, 2018b). The final data approved in that meeting for use in the Benchmark is the same used in this document. The SC meeting also approved a different assessment period (1988-2016). The assessment period was shortened relative to the previous assessment, which started in 1972, due to the quality of available data. The final approved data for the benchmark was the following:

-Commercial catch data:
- Total annual catches: 1988-2016. Presented in Table 1.
- Catch numbers-at-age: 1988-2001, 2006-2016, ages 1-8+. Presented in Table 2.
- Mean weight-at-age in catch (wcatch): 1988-2016, ages 1-8+. Presented in Table 3.

-Survey data: EU Flemish Cap survey data
- Index of stock abundance (in numbers) at age: 1988-2016, ages 1-8+. Presented in Table 4.
- Mean weight-at-age in the stock (wstock): 1988-2016, ages 1-8+. Presented in Table 5.
- Maturity-at-age: 1988-2016, ages 1-8+. Presented in Table 6.

In the mean weights, both for catch and stock, there were some gaps (missing values) in the data. The SC meeting agreed to fill those gaps with the mean of the previous and the following year.

Assessment methodology

A Bayesian SCAA model was applied to the data. Ages are from 1 to A+=8+ and years are from y=1 (1988) to Y=29 (2016). The cohorts are modelled forwards in time, starting from the recruits (age 1) in each year and abundance of each age 2-8+ in the first year, taking into account the natural and fishing mortality. The model equations are as follows:

1. **Recruits (age 1) each year**, N[y,1], for y=1,...,Y. The following prior is taken:

   $N[y,1] \sim LogN\ (\ median = medrec, CV = cvrec\ ),$

   - *medrec* and *cvrec* are some suitably chosen values.

2. **Numbers at age in the first year**, N[1,a], for a=2,...,A+. The following priors are taken:

   $N[1,a] \sim LogN\ (\ median = medrec\ \times\ e^{-\sum_{i=1}^{a-1}(M[1,i]+medF[i])}, CV = cvyear1\ )$, for *a=2,…,A-1*,

   $N[1,A+] \sim LogN\ (\ median = medrec\ \times\ \frac{e^{-\sum_{i=1}^{A-1}(M[1,i]+medF[i])}}{1-e^{-\ (M[1,A+]+medF[A+])}}, CV = cvyear1\ )$, for *a=A+,*

   - *medF[a]*, a=1,…A+, and *cvyear1* are some suitably chosen values.

3. **Forward population each year and age**, N[y,a], for y=2,...,Y and a=2,...,A+. Standard exponential decay equations:

   $N[y,a]\ =\ N[y-1,a-1]\ e^{-\ Z[y-1,a-1]}$, for *a=2,…,A-1*,

   $N[y,A+]\ =\ N[y-1,A-1]\ e^{-\ Z[y-1,A-1]} + N[y-1,A+]\ e^{-\ Z[y-1,A+]}$, for *a=A+*,

   $Z[y,a] = M[y,a] + F[y,a].$

4. **Fishing mortality is modelled as** *F[y,a]=f[y]*rC[y,a]*, for y=1,…,Y and a=1,…,A+.

   It is assumed that *rC(y,A+) = rC(y,A-1)* and that *rC(y, a=aref) =1*, for a chosen reference age *aref*.

   The factors *f[y]* and *rC(y,a)* are modelled as follows:

   a. ln(*f[y]*) is modelled as an AR(1) process over the years, with autocorrelation parameter *rhof*. The median and CV of the marginal prior distribution of *f[y]* in each year are *medf* and *cvf*, respectively.

      - *rhof* is assigned a Uniform(0,1) prior distribution,
      - *medf* and *cvf* are some suitably chosen values

   b. For each age different from *aref* and A+, ln(*rC[y,a]*) is modelled as random walk over the years, independently from age to age.

      The distribution in the first assessment year (y=1) is:

      $rC[1,a] \sim LogN(median = medrC[a], CV = cvrC[a]),$

      - *medrC[a]* and *cvrC[a]* are some suitably chosen values.

      The distribution in subsequent years (y>1) is given by a random walk in log scale:

      $\ln(\ rC[y,a]\ ) \sim N(mean = \ln(\ rC[y-1,a]\ )\ , \frac{1}{variance} = taurCcond[a])$

with $taurCcond[a]$ as follows:

- For the initial set of runs presented at the benchmark:
  $taurCcond[a] \sim Gamma(\, shape = s1.Ccond, rate = s2.Ccond)$
  where *s1.Ccond* and *s2.Ccond* are some suitably chosen values.
- The benchmark subsequently decided to fix the value of $taurCcond[a]$ so that it corresponds to a CV=20% for the conditional distribution of $rC[y,a]$.

5. **Observation equation for annual commercial total catch in weight**, Cton[y], for y=1,...,Y:

$$Cton[y] \sim LogN\,(\, median = \sum_{a=1}^{A+} mu.C[y,a] \times wcatch[y,a]\,, CV = cvCW\,),$$

$$mu.C[y,a] = N[y,a]\left(1 - e^{-Z[y,a]}\right)\frac{F[y,a]}{Z[y,a]}$$ is the standard Baranov catch equation,

- *cvCW* is some suitably chosen value. The chosen value corresponds to 95% probability of having no more than 15% deviation between the observed and the model-predicted annual catches.

6. **Observation equations for commercial catch numbers-at-age**, C[y,a], for each year y, excluding 2002 -2005, and age a=1,…,A+:

$$\ln(\, C[y,a]\,) \sim N(\, mean = \ln(\, mu.C[y,a]\,)\,, \frac{1}{variance} = psi.C[a]\,)$$

with $psi.C[a]$ as follows:

- For the initial set of runs presented at the benchmark:
  $psi.C[a] \sim Gamma(\, shape = s1.C, rate = s2.C\,)$
  where *s1.C* and *s2.C* are some suitably chosen values.
- The benchmark subsequently decided to fix the value of $psi.C[a]$ so that it corresponds to a CV=20% for the observation equation of catch numbers-at-age.

7. **Observation equations for survey indices**, CPUE.EU[y,a], y=1,…,Y and a=1,…,A+:

$$\ln(\, CPUE.EU[y,a]\,) \sim N(\, mean = \ln(\, mu.CPUE.EU[y,a]\,)\,, \frac{1}{variance} = psi.EU[a]\,)$$

where

$$mu.CPUE.EU[y,a] = phi.EU[a]\left\{N[y,a]\,\frac{\exp(-alpha.EU*Z[y,a]) - \exp(-alpha.EU*Z[y,a])}{(beta.EU - alpha.EU)*Z[y,a]}\right\}^{gama.EU[a]},$$

alpha.EU=0.50 and *beta.EU*=0.58 correspond to the timing of the survey (July),

<u>Prior on $phi.EU[a]$:</u>

$$\ln(\, phi.EU[a]\,) \sim N(\, mean = medlogphi, \frac{1}{variance} = taulogphi\,),$$

- *medlogphi* and *taulogphi* are some suitably chosen values,

<u>Prior on $gama.EU[a]$:</u>

For ages a in the set *adep*, $gama.EU[a]$ = 1, whereas for other ages a:

$gama.EU[a] \sim N(\,mean = medgama, \frac{1}{variance} = taulogama),$

- *medgama* and *taugama* are some suitably chosen values,

Prior on $psi.EU[a]$:

- For the initial set of runs presented at the benchmark:
  $psi.EU[a] \sim Gamma(\,shape = shpsi, rate = rtpsi)$
  where *shpsi* and *rtpsi* are some suitably chosen values.
- The benchmark subsequently decided to fix the value of $psi.EU[a]$ so that it corresponds to a CV=30% for the observation equation of survey index of numbers-at-age

Different scenarios (37) with this model changing some of the settings and/or input data were run for the NAFO 3M cod benchmark that took place in April. Model settings common to all the runs are presented in Table 7. Seven more scenarios were run after the benchmark following its recommendations, mainly regarding the prior distribution of recruitment and CVs of population abundance in initial year.

In the model, *M* can be treated as one value, a vector or a matrix; and it can be fixed or be assigned a prior distribution. In the configuration favoured by the benchmark, M is a vector (i.e. age-dependent, constant over the years), which follows a log-Normal prior distribution for each age. The prior median for each age was assigned based on life-history considerations and outcomes from explorations of the multispecies GadCap model; a 15% prior CV was used.

Given the very low catch numbers observed at age 1 (see Table 2), the benchmark decided to set the catch at age 1 data equal to zero in all years and to assume in the model that F at age 1 is equal to zero. The benchmark also decided to treat as NAs the zeros observed in the survey abundance indices at age (very few zeros; see ages 1-8+ in Table 4) and those observed in the catch at age matrix for ages > 1 (a few zeros; see Table 2). This procedure on the data was not applied in the initial set of runs presented at the benchmark (in those earlier runs, zeros had been replaced by very low values); only to those runs conducted after the benchmark decision was taken.

The complete list of scenarios run is provided in Table 10. The rationale of each of the parameters is the following:

- $taurCcond[a]$: this parameter controls the variability (CV) of the prior of the selectivity (rC) between years. It can be selected to be different for each age or the same for groups of ages. If *S2.Ccond* is fixed at 0.04, then *S1.Ccond*=4 results in the median of the prior distribution of this CV being 10%, whereas *S1.Ccond*=0.75 results in the prior median of the CV being 30%.

-*psi.C[a]*: this parameter controls the variability (CV) of the observation equations for catch numbers-at-age. It can be selected to be different by age or grouped by groups of ages. The higher the value of this parameter, the closer the model must follow the abundance catch-at-age (so, closer to an XSA is the model).

-*psi.EU[a]*: this parameter controls the variability (CV) of the observation equation for the survey abundance index at age. It can be selected to be different by age or grouped by groups of ages.

-*phi.EU[a]* (qs): these are the catchabilities of the surveys by age. They can be all different or can be grouped by groups of ages.

-*CVs*: four different CVs were changed in the runs conducted at the benchmark: cvrec (CV over the annual recruitment), cvyear1 (CV over the numbers by age in the first year), cvf (the CV over f) and cvrC (the CV over rC, so, selectivity by age and year; this is related to the model parameter $taurCcond[a]$).

-*adep*: this is the set of ages for which the survey catchability depends on population abundance (see Table 10); so gama.EU=1 for all ages not belonging to the set *adep*.

-*Y/Y-1*: last year used in the calculation of the catch-at-age (see Table 10; it should have been Y in all runs, but was Y-1 in some of them due to an oversight).

-*Zeros*: if the zeros in the catch at age and in the survey index are included as zeros (actually, they were replaced by very low values) or treated as NAs (see Table 10 and the discussion earlier in this document about benchmark decision).

-*medrec*: this parameter is the median of the prior distribution for the recruitment.

-*cvrec*: this parameter controls the variability (CV) of the prior distribution for the recruitment.

-*cvyear1* this parameter controls the variability (CV) of the prior distribution for the abundance in the first year.

In order to compare between scenarios, an attempt to calculate the deviance information criterion (DIC) was made. DIC is a hierarchical modeling generalization of the Akaike information criterion (AIC) and the Bayesian information criterion (BIC). It is particularly useful in Bayesian model selection problems where the posterior distributions of the models have been obtained by Markov chain Monte Carlo (MCMC) simulation. The idea is that models with smaller DIC should be preferred to models with larger DIC. However, we found the calculation of the DIC inside the model to be unstable: running twice the model with the same settings, the DIC changed between runs. It is not clear that this is working reliably to choose model settings, and it could perhaps be better to let the choice be guided by the biological rationale underlying the settings considered in each run.

All the runs were made in Jags called from R via the package rjags.

Results

All the models reach the convergence after 100,000 iterations, from which 1000 are taken for the results.

The approach followed to explore potential scenarios was to start the first runs allowing the model to estimate all the parameters independently (resulting in many parameters to estimate) and then, looking at the results and using the available biological and fishery information, to try and reduce the number of parameters fitted by the model.

With regards to **catchability** in the survey (*phi.EU[a])*, we tried different settings for this. In R1 and R2 we have catchability different for all ages, and examining the posterior distribution of the catchabilities in R1 (Figure 1), it can be observed that some of the ages have similar catchabilities. To see the differences, we tried four different age groupings for the catchability: 1,2,3-6,7-8+; 1,2-8+; 1,2,3-8+; 1,2,3,4-8+. The DIC for these four groupings are quite similar and, based on the biological and survey gear information, we have chosen to group the ages as follows: 1, 2, 3 and 4-8+. This setting was used in all runs starting from R37.

The CV of the observation equation of the **catch-at-age** can be estimated (including a prior) or can be assigned a fixed value, and it can be different by age or grouped by groups of ages. We tried here four different approaches: CVs different for all ages, CVs equal for all ages, CVs grouped by ages 1-2, 3-6, 7-8+, or CV fixed for all the ages. When we take all the CVs to be equal, the SSB increases incredibly (R5 and R6) (Figure 8). Examining the prior and posterior of R19 (Figure 2), in which we have the CVs of all ages different, we can see that for ages 3 to 7 the posterior of the CV is around 30%, but for ages 1, 2 and 8+ the estimated CV value is not consistent as it is too high. It is, therefore, necessary to force the model to reduce the CV in those ages, and the best way to do that seems to be to force the CVs to be equal by groups of ages. The age groups 1-2, 3-6 and 7-8+ seem to be quite logical, as the bulk of the catches is always between 3 and 6, so the CV of those ages probably is smaller, while ages 1 and 2 and ages 7 and 8+ are less represented in the catch and so the CV must be different. But if we look at the prior and posterior of R20 (Figure 3), it is still a problem with the CVs of ages 1, 2, 7 and 8+, that are still too high. To deal with this, the benchmark decided to fix this CV at 20% for all ages, and this was the value used in the all runs starting from R32. A CV of 20% seems reasonable for the catch-at-age of this stock taking into account their variability.

A parameter related to the CV of the observation equation of catch-at-age is *S1.C* (see equations earlier in this document for technical detail). We think that 4 is a sensible value for this parameter, as it results in a CV of around 30% for the observed catch-at-age, but we made a run with a much higher value of this parameter (100) in order to force the model to follow the observed catch-at-age, similarly to what the XSA does. The results in SSB for this run (R8) are similar to the Bayesian XSA approved in June 2017 (Figure 9). In the last runs, as the CV of the catch-at-age is fixed, this parameter does not exist in the model.

For the CV of the observation equation of the **EU survey indices**, we tried different age groupings: all different, all equal, 1,2,3-8+ and 1,2-8+. If we take all different, as in the R19 (Figure 4), we can see that the CVs between 2 and 6 are quite stable, but high for ages 1, 7 and 8+. As this is a survey, it seems reasonable to have all ages well represented except for age 1. Therefore, an appropriate approach could be to have different CV values for age 1 and for ages 2-8+. But as in the case of the catch-at-age CV, the benchmark decided that in order to have CVs in a range of values that seems logical, it was better to fix this value to be 30%. A CV of 30% seems reasonable for the survey abundance index of this stock, taking into account their variability. As the survey only covers one month by year, a CV higher than the one chosen for the catch-at-age seems reasonable.

With regards to the interannual variability in the prior of the **selectivity by age** (related to *taurCcond* parameter) we have tried different age groups: all different, all equal, and 1,2-8+ (always excluding age 5, the reference age for selectivity in the model). If we allow the variability to be different for all the ages, as in R10, the CV of most ages is extremely high, particularly for ages 1 and 2 (Figure 5). If we instead take just two groups, 1,2-8+, as in R19, we can see that, although the CV is still very high, particularly for age 1, it is one of the lowest if we look to all the runs (Figure 6). Based on these findings, the benchmark decided that in order to have CVs in a range of values that seem logical, it was better to fix this value at 20%.

A parameter related to the interannual variability in selectivity is *S1.Ccond* (see equations earlier in this document for technical detail). Although we started the runs with a value of *S1.Ccond* corresponding to a prior distribution for the CV centred at 10% (R1), taking into account the great variation over the years in the selectivity we think that, in the case of having a prior over the CV (i.e. over the interannual variability in selectivity), it is more logical to center such a prior at around 30% (R2-27, 30-31). In the last runs, as the CV of the selectivity is fixed, the *S1.Ccond* parameter does not exist in the model. The great interannual variability in the selectivity is mainly due to the closure of the fishery between 1999 and 2009, when the catches were mainly by-catch of other fisheries.

With regards to the **first age** for which the survey catchability is independent of population abundance (so, gama.EU=1), we have tried two different approaches: catchabilities of ages 1 and 2 dependent on abundance and only age 1 catchability dependent on abundance. It was decided to use only age 1 dependent on abundance. The rationale for this decision is that when we use ages 1 and 2, the posterior median of the distribution of gama.EU at age 2 is almost equal to 1 and the distribution is quite narrow (Figure 7), so it seems reasonable to fix gama.EU for age 2 at 1, as for the ages 3-8+.

We have tried four different values for two different **CVs** (*cvf* and *cvrC*), namely 1, 2, 4 and 16 (100%, 200%, 400% and 1600%). We think that the values 1 and 2 are a bit small for our data and 16 a bit high, so the best one seems to be 4.

During the March SC meeting on input data (by WebEx), it was decided to try three different approaches for **M**: a single value for all ages and years, a vector by age constant by year, and a matrix variable by age and year. The values used are in Table 8 and come from González-Costas and González-Troncoso (2018) and the results of the GADGET (SCR 18/XX). During the benchmark, it was decided to run some scenarios for which the M was not a fixed input but an output of the model (i.e. estimated) via a prior, as in the approved Bayesian XSA model (González-Troncoso, 2017). In this context, two different settings were analyzed: M with one prior with median equal to 0.19 (M equal for all ages and years), and M with eight priors, one for each age, with median equal to the fixed vector used in previous runs (M equal for all years but different by age). The posterior median of two of the scenarios, R32 and R37, are presented in Table 9. It can be seen that, when we allow the M to be different between ages, the value for age 1 is much higher than for the rest of the ages. For ages 2 and 3 it is still high, and then it decreases to increase again a bit at age 8. Based on the biological information available for this stock (cannibalism, age composition, etc), this seems more logical than having a single value for all ages, so the benchmark decided to use this approach in the last runs (starting from R37).

In the first scenarios run, the catch-at-age data were used in the model until year Y-1 instead of Y. This was an oversight and was fixed after R19.

There are some zeros in the catch-at-age in numbers (Table 2) and in the EU index-at-age (Table 4), particularly in the older ages. As having these zeros in the data seems to be a sampling issue more than the reality, the benchmark decided to replace them in the data by NAs. This approach was used in the last scenarios (R32, R33, >R37).

With regards to the prior median of the annual **recruitment**, a value of 15000 was set in the first runs, as it was the value used in the last approved assessment. This value was chosen in 2008 taking into account the recruitments of the previous years. During the benchmark, examining the results of the Bayesian SCAA model, a more logical value of 45000 was set taking into account the recent recruitments of this stock that in almost all scenarios and almost all years are well above 15000, and the fact that M is now centred around considerably larger values than used in previous assessments, particularly for age 1. To try and prevent the prior distribution for recruitment to have undue impact on model results, it was considered appropriate to increase the CV of the prior distribution from the originally considered values (2 and 4) to 10, i.e. 1000%.

The CV of the prior distribution of the **numbers-at-age in the first year** was set at various values between 1 and 16. The benchmark recommended exploring a scenario with this CV set to 10 (1000%).

In Figure 8 the DIC results are shown by means of penalized deviance. The figure shows much larger DIC values for R28, R29 and R34-R36. It seems that, when we introduce a prior over the M, having 0 in the catch numbers-at-age and in the EU survey index-at-age produces a great increase in the DIC. As noted above, these zeros are a sampling matter and not biologically reasonable, so it is better to fill them with NAs or by the mean of surrounding values.

After looking to all the scenarios run and with the modifications made during the benchmark, and based on the knowledge and information about the fishery and the survey, the SC decided that the base case to be presented to the June SC meeting should have a structure similar to R37; however, it was noted that it would be more appropriate to use medrec=45000 and cvyear1=10 and that a full set of diagnostics would be needed for the modified R37 run. This led to developing R39-42 for this document.

Table 11 and Figure 9 show the median posterior SSB for all the scenarios run (R1-R44)); the values for year 2016 are displayed in Figure 15. As there are too many runs, we select some of them which are considered more representative of the different behaviours encountered. To select them, the run settings and the results in the SSB were taken into account. Therefore, we have the rest of the plots for the following runs: R5, R8, R16, R19, R21, R22, R23, R28, R31, R37, R39 and R42. Figures 10-14 show the total B, the SSB, the R, the F_{bar} and the Number at age for each of the scenarios, respectively.

Table 11 presents the posterior median of the SSB for all the scenarios R1-R44 and in Figure 15 the same value for year 2016. It is remarkable the difference between R14, R15 and R16. The three scenarios have exactly the same parameters except for the CVs of several distributions, with these CVs being 2 (R14), 4 (R15) and 16 (R16); see Table 10. In particular, the difference between R14 and the other two is quite large. To try and understand the origin of this behavior, another four runs were made (R24-R27), changing progressively the value of the CVs from 2 to 4 for the various distributions (Table 10). The median SSB results are plotted in Figure 15 and show that the difference in the SSB comes from the change in the CV of the selectivity.

Concerning the SSB estimates for recent years, we note that R5 and R6 result in substantially larger estimates and R8 and R29 in substantially smaller estimates than the rest of the runs. Excluding these 4 runs, all others produce estimates of SSB in 2016 ranging between 66000 and 127000 tons. The base case at the time the benchmark ended, R37, estimates this SSB at 93000 t, whereas the modified run following the benchmark's suggestions (R42) estimates this SSB at 95000 t.

Retrospective pattern

A 5-years retrospective analysis was made for Run 37 and R42. Results are shown in Figure 16 and Figure 17. No evident patterns can be seen, although there is a revision downwards of the big 2009-2011 year classes as more years of data are added into the assessment.

Comparison with the last approved assessment

Figures 18-21 show the comparison between the results of the R42 of the Bayesian SCAA and the approved assessment in June 2017. In order to compare the results, only the results of period 1988-2016 for the last approved assessment are shown, taking into account that this assessment was performed for the period 1972-2016.

The Bayesian SCAA is a forwards model, while the Bayesian XSA is a backwards model. For this reason, the priors in the case of the Bayesian SCAA are put in the first year of the assessment, and in the case of the Bayesian XSA in the last year of the assessment.

The SSB of both models differs since approximately 2005, the difference being bigger in recent years (Figure 18). The SSB for 2016 estimated in R42 is 3.5 times the SSB estimated in the last approved assessment. Taking a look at the number at age in Figure 21, we can see that the differences come from all ages, but mainly from ages older than 4 years.

The recruitment in general is quite higher for the Bayesian SCAA R42, which probably arises as a consequence of various aspects, such as the higher values of M and the way the SCAA model weighs the different datasets compared to the XSA (e.g. the SCAA model allows departures from the observed catch-at-age data). The F_{bar}(3-5) is lower for the Bayesian SCAA, being this logical as we are estimating higher population abundance with the same catch.

One of the outputs that probably make the difference in the level of SSB between both models is the survey catchability. Figure 22 show the catchabilities by age for both models. Take into account that the XSA estimates the catchabilities to be different for all ages (1-8+), while the SCAA groups the ages (1, 2, 3 and 4-8+). We can see that in some ages, the catchability in the XSA is almost twice than in the SCAA. For that, the abundance at age in the last year are bigger for the SCAA that for the XSA, giving bigger SSB.

References

Cerviño, S. and A. Vázquez, 2003. Re-opening criteria for Flemish Cap cod: a survey-based method. NAFO SCR Doc. 03/38. Serial Number N4856.

Fernández, C., S. Cerviño and A. Vázquez, 2007. A Survey-based assessment of cod in division 3M. NAFO SCR Doc. 07/39. Serial Number N5526.

Fernández, C., S. Cerviño and A. Vázquez, 2008. Assessment of the Cod Stock in NAFO Division 3M. NAFO SCR Doc. 08/26. Serial Number N5391.

González-Costas, F. and D. González-Troncoso, 2018. Cod 3M Natural Mortality. NAFO SCR Doc. 18/003. Serial Number N6780.

González-Troncoso, 2017. Assessment of the Cod Stock in NAFO Division 3M. NAFO SCR Doc. 17/38. Serial Number N6693.

NAFO, 2018a. Report of the benchmark. NAFO SCS Serial Doc. 18/XX, Serial Number No. NXXXX.

NAFO, 2018b. Report of the review of input data for 3M cod benchmark assessment. NAFO SCS Serial Doc. 18/04, Serial Number No. N6783.

Pérez-Rodríguez. A., 2018. Estimates of natural predation and residual mortality for the Flemish Cap cod NAFO SCR Doc. 18/XX. Serial Number XXXX.

Vázquez, A. and S. Cerviño, 2005. A review of the status of the cod stock in NAFO division 3M. NAFO SCR Doc. 05/38. Serial Number N5124.

Acknowledges

This research was partially funded by the European Union founds under the Framework Contract No EASME/EMFF/2016/008 **-** "provision of scientific advice for fisheries beyond EU waters"**-** Specific Contract No 03 (SI2.753135) "Support to a robust model assessment, benchmark and development of a Management Strategy Evaluation for cod in NAFO Division 3M".

Table 1. Total commercial cod catch in Division 3M. Reported nominal catches since 1960 and estimated total catch from 1988 to 2016 in tons.

Year	Estimated[2]	Portugal	Russia	Spain	France	Faroes	UK	Poland	Norway	Germany	Cuba	Others	Total[1]
1960		9	11595	607					46	86		10	12353
1961		2155	12379	851	2626		600	336		1394		0	20341
1962		2032	11282	1234			93	888	25	4		349	15907
1963		7028	8528	4005	9501		2476	1875				0	33413
1964		3668	26643	862	3966		2185	718	660	83		12	38797
1965		1480	37047	1530	2039		6104	5073	11	313		458	54055
1966		7336	5138	4268	4603		7259	93		259		0	28956
1967		10728	5886	3012	6757		5732	4152		756		46	37069
1968		10917	3872	4045	13321		1466	71				458	34150
1969		7276	283	2681	11831					20		52	22143
1970		9847	494	1324	6239		3	53				35	17995
1971		7272	5536	1063	9006			19		1628		25	24549
1972		32052	5030	5020	2693	6902	4126	35	261	506		187	56812
1973		11129	1145	620	132	7754	1183	481	417	21		18	22900
1974		10015	5998	2619		1872	3093	700	383	195		63	24938
1975		10430	5446	2022		3288	265	677	111	28		108	22375
1976		10120	4831	2502	229	2139		898	1188	225		134	22266
1977		6652	2982	1315	5827	5664	1269	843	867	45	1002	553	27019
1978		10157	3779	2510	5096	7922	207	615	1584	410	562	289	33131
1979		9636	4743	4907	1525	7484		5	1310		24	76	29710
1980		3615	1056	706	301	3248		33	1080	355	1	62	10457
1981		3727	927	4100	79	3874			1154			12	13873
1982		3316	1262	4513	119	3121	33		375			14	12753
1983		2930	1264	4407		1489			111	3		1	10205
1984		3474	910	4745		3058			47	454	5	9	12702
1985		4376	1271	4914		2266			405	429	9	5	13675
1986		6350	1231	4384		2192				345	3	13	14518
1987		2802	706	3639	2300	916						269	10632
1988	28899	421	39	141		1100					3	14	1718
1989	48373	170	10	378								359	917
1990	40827	551	22	87		1262						840	2762
1991	16229	2838	1	1416		2472	26		897		5	1334	8989
1992	25089	2201	1	4215		747	5				6	51	7226
1993	15958	3132	0	2249		2931						4	8316
1994	29916	2590	0	1952		2249			1			93	6885
1995	10372	1641	0	564		1016						0	3221
1996	2601	1284	0	176		700	129			16		0	2305
1997	2933	1433	0	1			23					0	1457
1998	705	456	0									0	456
1999	353	2	0									0	2
2000	55	30	6									0	36
2001	37	56	0									0	56
2002	33	32	1									0	33
2003	16	7	0									9	16
2004	5	18	2									3	23
2005	19	16	0			7						3	26
2006	339	51	1	16								55	123
2007	345	58	6	33								28	125
2008	889	219	74	42	3	0						63	401
2009	1161	856	87	85		22						122	1172
2010	9291	1345	374	921		1183	761		514			147	5245
2011	12836	2412	655	1610	200	2211	1063		1301		185	340	9977
2012	12836	2593	745	1597	131	2045	868		809		172	108	9068
2013	13985	4427	896	2380		2723	1328		1322			445	13521
2014	14290	5345	950	2099		3370		393	1344			855	14356
2015	13785	4680	893	1999		3319			1296			641	12828
2016	14023	5958	893	1232		3124	1198		1318			72	13795

[1] Recalculated from NAFO Statistical data base using the NAFO 21A Extraction Tool
[2] STACFIS estimates

Table 2. Catch-at-age (thousands).

	1	2	3	4	5	6	7	8+
1988	1	3500	25593	11161	1399	414	315	162
1989	0	52	15399	23233	9373	943	220	205
1990	7	254	2180	15740	10824	2286	378	117
1991	1	561	5196	1960	3151	1688	368	76
1992	0	15517	10180	4865	3399	2483	1106	472
1993	0	2657	14530	3547	931	284	426	213
1994	0	1358	28303	9218	430	206	16	203
1995	0	0	192	4773	2003	474	98	169
1996	0	81	714	311	1072	88	0	0
1997	0	0	1016	956	179	359	60	0
1998	0	0	8	170	286	30	19	2
1999	0	0	15	15	96	60	3	1
2000	0	0	54	1	1	4	1	0
2001	0	9	0	4	2	0	2	2
2002								
2003								
2004								
2005								
2006	0	22	19	81	2	10	2	0
2007	0	2	30	1	27	1	14	5
2008	1	89	136	133	3	40	1	3
2009	0	23	51	210	108	0	32	7
2010	34	452	1145	1498	808	388	4	103
2011[1]	18	537	1608	701	1144	961	354	275
2012[1]	39	389	1443	834	1013	739	357	344
2013	22	646	4169	962	1124	755	521	388
2014	7	13	730	4131	1464	871	556	405
2015	0	94	402	1548	1457	2596	602	480
2016	0	40	883	731	1822	1167	939	757

Table 3. Weight-at-age (kg) in catch. In red, the filled cero values.

	1	2	3	4	5	6	7	8+
1988	0.058	0.198	0.442	0.821	2.190	3.386	5.274	7.969
1989	0.069	0.209	0.576	0.918	1.434	2.293	4.721	7.648
1990	0.080	0.153	0.500	0.890	1.606	2.518	3.554	7.166
1991	0.118	0.229	0.496	0.785	1.738	2.622	3.474	6.818
1992	0.115	0.298	0.414	0.592	1.093	1.704	2.619	3.865
1993	0.115	0.210	0.509	0.894	1.829	2.233	3.367	4.841
1994	0.112	0.248	0.649	0.973	1.686	2.331	3.008	4.898
1995	0.112	0.248	0.649	0.973	1.686	2.331	3.008	4.898
1996	0.110	0.286	0.789	1.051	1.543	2.429	2.730	4.653
1997	0.107	0.360	0.754	1.038	1.506	2.115	2.451	4.408
1998	0.098	0.472	0.719	1.024	1.468	1.800	2.252	3.862
1999	0.098	0.472	0.920	1.298	1.848	2.436	3.513	4.893
2000	0.098	0.583	0.672	1.749	2.054	2.836	3.618	5.055
2001	0.098	0.481	0.998	1.696	2.560	3.303	3.905	5.217
2002	0.098	0.588	1.323	1.388	2.572	3.770	5.158	5.603
2003	0.098	0.462	1.063	1.455	2.978	3.696	5.859	6.120
2004	0.098	0.839	1.677	2.009	3.353	5.576	6.241	8.273
2005	0.098	0.895	1.618	2.368	3.259	4.767	6.177	6.553
2006	0.098	1.081	1.462	2.283	3.966	5.035	6.332	7.997
2007	0.098	0.974	1.858	3.388	4.062	6.128	6.809	9.440
2008	0.088	0.448	1.364	3.037	3.498	5.248	6.643	8.251
2009	0.172	0.507	1.026	2.087	3.727	4.810	5.900	9.534
2010	0.162	0.700	1.279	1.829	2.764	4.372	4.199	8.575
2011	0.086	0.396	0.939	1.522	2.228	3.560	5.980	8.753
2012	0.086	0.374	0.990	1.491	2.136	3.583	6.183	9.183
2013	0.007	0.284	0.762	1.305	2.112	2.990	4.530	8.564
2014	0.108	0.203	0.538	1.108	1.809	2.874	4.087	7.671
2015	0.085	0.261	0.531	0.857	1.370	1.938	3.570	6.252
2016	0.085	0.191	0.550	0.787	1.237	2.157	3.439	6.719

Table 4 EU bottom trawl survey abundance at age and total (thousands) and total biomass (tons).

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	Total Abundance	Total Biomass
1988	4868	79905	49496	13448	1457	211	225	72	0	0	0	0	0	0	0	0	149683	40839
1989	19604	10800	91303	54613	20424	1336	143	126	6	7	0	0	0	0	0	0	198363	114050
1990	2303	12348	5121	16952	15834	4492	340	146	77	25	0	0	0	0	0	0	57637	59362
1991	129032	26220	16903	2125	6757	1731	299	68	32	4	10	0	0	0	0	0	183181	40248
1992	71533	41923	5578	2385	385	1398	244	14	0	0	8	0	0	0	0	0	123468	26719
1993	4075	138357	31096	1099	1317	173	489	87	0	0	0	0	0	0	0	0	176693	60963
1994	3017	4130	27756	5097	130	67	7	111	0	5	0	0	0	0	0	0	40319	26463
1995	1425	11901	1338	3892	928	33	23	0	21	5	0	0	0	0	0	0	19567	9695
1996	36	3121	6659	892	2407	192	8	5	0	0	0	0	0	0	0	0	13320	9013
1997	37	150	3478	4803	391	952	21	0	0	0	0	4	0	0	0	0	9837	9966
1998	23	83	95	1256	1572	78	146	0	6	0	0	0	0	0	0	0	3259	4986
1999	5	84	116	117	717	444	19	5	0	0	0	0	0	0	0	0	1507	2854
2000	178	16	327	198	96	446	172	11	17	0	0	5	0	5	0	0	1470	3062
2001	473	1990	13	122	79	15	142	99	6	6	6	0	0	0	0	0	2951	2695
2002	0	1330	641	29	70	33	26	96	30	0	5	0	0	0	0	0	2261	2496
2003	684	54	628	134	22	42	7	8	39	24	0	0	0	0	0	0	1642	1593
2004	14	3380	25	600	168	5	10	3	5	15	0	0	0	0	0	0	4226	4071
2005	8069	16	1118	78	709	136		17	16	8	0	0	0	0	0	0	10166	5242
2006	19709	3886	62	1481	85	592	115	7	0	7	14	0	7	0	0	0	25965	12505
2007	3917	11620	5022	21	1138	58	425	74	13	20	0	0	0	0	0	0	22308	23886
2008	6096	16671	12433	4530	72	946	56	231	76	0	14	0	0	0	0	0	41124	43676
2009	5139	7479	16150	14310	4154	26	1091	0	335	0	0	14	0	0	0	0	48697	75228
2010	66370	27689	8654	7633	4911	1780	8	442	46	251	26	0	0	0	0	0	117810	69295
2011	347674	142999	16993	6309	7739	3089	1191	0	215	0	89	0	0	0	0	0	526300	106151
2012	103494	128087	10942	11721	4967	4781	1630	832	24	93	30	101	0	17	0	0	266720	113227
2013	5525	67521	32339	4776	4185	2782	1807	963	278	40	29	32	5	0	0	0	120280	72289
2014	7282	2372	48564	43168	17861	6842	3447	1931	1551	600	79	54	8	0	0	0	133760	159939
2015	1141	12952	7250	25614	14107	21854	3434	1426	762	366	194	14	21	21	0	7	89164	114807
2016	56	4485	14356	2230	14540	12375	4814	1157	522	303	145	28	20	0	0	0	55032	80583

Table 5. Weight-at-age (kg) in stock. In red, the filled cero values.

	1	2	3	4	5	6	7	8+
1988	0.032	0.106	0.308	0.664	1.970	3.500	5.742	6.954
1989	0.036	0.101	0.330	0.836	1.293	2.118	4.199	7.360
1990	0.043	0.181	0.354	0.868	1.566	2.507	4.132	6.572
1991	0.056	0.171	0.501	0.865	1.594	2.593	3.423	6.182
1992	0.056	0.247	0.485	1.394	1.723	2.578	3.068	9.406
1993	0.043	0.227	0.657	1.216	2.279	2.381	3.373	5.731
1994	0.063	0.214	0.599	1.321	2.132	4.054	4.119	6.555
1995	0.048	0.243	0.479	0.969	1.851	2.680	5.532	7.309
1996	0.044	0.260	0.544	0.813	1.331	2.252	4.079	5.118
1997	0.081	0.333	0.652	1.020	1.327	2.092	1.997	9.717
1998	0.073	0.371	0.773	1.206	1.684	2.015	3.070	7.525
1999	0.108	0.398	0.946	1.329	1.866	2.444	3.461	4.987
2000	0.106	0.606	0.971	1.638	1.940	2.860	3.461	7.985
2001	0.084	0.493	1.281	1.724	2.588	3.488	3.893	5.137
2002	0.071	0.440	1.191	1.540	2.661	3.916	5.302	5.672
2003	0.058	0.337	0.926	1.566	3.047	3.769	5.721	6.451
2004	0.004	0.620	1.488	2.098	3.332	4.808	6.207	7.886
2005	0.084	0.580	1.256	2.242	2.875	4.187	6.033	8.148
2006	0.096	0.720	1.096	2.549	3.644	4.777	5.858	9.691
2007	0.053	0.609	1.640	3.478	4.097	5.787	6.373	8.315
2008	0.068	0.382	1.344	2.695	3.191	5.015	6.324	7.938
2009	0.078	0.407	0.976	2.072	3.881	6.958	6.583	9.461
2010	0.061	0.384	1.089	1.677	2.956	5.379	7.616	9.144
2011	0.038	0.211	0.913	1.618	2.339	3.594	6.050	9.396
2012	0.074	0.369	0.726	1.349	1.988	2.656	4.933	7.812
2013	0.071	0.175	0.687	1.159	2.004	2.750	4.206	7.614
2014	0.048	0.169	0.354	1.059	1.623	2.536	3.846	8.444
2015	0.049	0.156	0.469	0.747	1.216	1.847	3.434	6.775
2016	0.044	0.169	0.412	0.783	1.304	2.024	2.883	6.905

Table 6. Maturity at age and age of first maturation (median values of ogives).

	1	2	3	4	5	6	7	8+	a50
1972	0.000	0.000	0.000	0.002	0.507	0.998	1.000	1.000	5.00
1973	0.000	0.000	0.000	0.002	0.507	0.998	1.000	1.000	5.00
1974	0.000	0.000	0.000	0.002	0.507	0.998	1.000	1.000	5.00
1975	0.000	0.000	0.000	0.002	0.507	0.998	1.000	1.000	5.00
1976	0.000	0.000	0.000	0.002	0.507	0.998	1.000	1.000	5.00
1977	0.000	0.000	0.000	0.002	0.507	0.998	1.000	1.000	5.00
1978	0.000	0.000	0.000	0.002	0.507	0.998	1.000	1.000	5.00
1979	0.000	0.000	0.000	0.008	0.154	0.813	0.991	1.000	5.54
1980	0.000	0.000	0.002	0.029	0.302	0.862	0.989	1.000	5.31
1981	0.000	0.000	0.005	0.104	0.716	0.982	0.999	1.000	4.70
1982	0.000	0.000	0.007	0.146	0.809	0.991	1.000	1.000	4.55
1983	0.000	0.000	0.007	0.146	0.809	0.991	1.000	1.000	4.55
1984	0.000	0.000	0.007	0.146	0.809	0.991	1.000	1.000	4.55
1985	0.000	0.000	0.007	0.146	0.809	0.991	1.000	1.000	4.55
1986	0.000	0.000	0.007	0.146	0.809	0.991	1.000	1.000	4.55
1987	0.000	0.000	0.007	0.146	0.809	0.991	1.000	1.000	4.55
1988	0.054	0.099	0.175	0.291	0.441	0.603	0.745	0.879	5.36
1989	0.054	0.099	0.175	0.291	0.441	0.603	0.745	0.879	5.36
1990	0.054	0.099	0.175	0.291	0.441	0.603	0.745	0.879	5.36
1991	0.018	0.045	0.111	0.247	0.463	0.687	0.849	0.951	5.16
1992	0.002	0.011	0.048	0.184	0.503	0.819	0.953	0.993	4.99
1993	0.001	0.007	0.049	0.282	0.751	0.959	0.994	1.000	4.46
1994	0.000	0.001	0.050	0.657	0.986	1.000	1.000	1.000	3.82
1995	0.000	0.000	0.006	0.803	1.000	1.000	1.000	1.000	3.79
1996	0.000	0.000	0.029	0.666	0.993	1.000	1.000	1.000	3.84
1997	0.000	0.008	0.111	0.670	0.971	0.998	1.000	1.000	3.75
1998	0.000	0.002	0.096	0.874	0.998	1.000	1.000	1.000	3.54
1999	0.000	0.001	0.130	0.902	0.999	1.000	1.000	1.000	3.46
2000	0.000	0.001	0.160	0.971	1.000	1.000	1.000	1.000	3.34
2001	0.000	0.001	0.315	0.998	1.000	1.000	1.000	1.000	3.12
2002	0.000	0.010	0.636	0.997	1.000	1.000	1.000	1.000	2.89
2003	0.001	0.024	0.513	0.978	0.999	1.000	1.000	1.000	2.99
2004	0.000	0.000	0.100	0.967	1.000	1.000	1.000	1.000	3.40
2005	0.041	0.171	0.502	0.830	0.959	0.991	0.998	1.000	3.00
2006	0.000	0.014	0.365	0.959	0.999	1.000	1.000	1.000	3.15
2007	0.000	0.012	0.261	0.920	0.997	1.000	1.000	1.000	3.31
2008	0.000	0.012	0.231	0.882	0.995	1.000	1.000	1.000	3.37
2009	0.000	0.010	0.181	0.830	0.991	1.000	1.000	1.000	3.49
2010	0.000	0.009	0.167	0.812	0.989	1.000	1.000	1.000	3.52
2011	0.001	0.008	0.072	0.428	0.878	0.986	0.999	1.000	4.13
2012	0.000	0.000	0.018	0.578	0.990	1.000	1.000	1.000	3.93
2013	0.004	0.037	0.285	0.804	0.977	0.998	1.000	1.000	3.39
2014	0.000	0.003	0.046	0.400	0.902	0.992	0.999	1.000	4.15
2015	0.000	0.000	0.004	0.117	0.794	0.991	1.000	1.000	4.60
2016	0.000	0.000	0.004	0.047	0.393	0.894	0.991	1.000	5.17

Table 7. Unchanged parameters in the priors of the Bayesian SCAA. These parameters are common to all the runs for which the parameter is applicable.

Parameter	Value	Parameter	Value
medF	c(0.0001,0.1,0.5,0.7,0.7,0.7,0.7,0.7)	*rtpsi*	0.07
cvCW	0.08	*alpha.EU*	0.5
S2.C	0.345	*beta.EU*	0.58
medlogphi	0	*medf*	0.2
taulogphi	1/5	*rhofmin*	0
medgama	1	*aref*	5
taugama	1/0.25	*medrC*	c(0.001,0.3,0.6,0.9,1,1,1)
shpsi	2	*S2.Ccond*	0.04

Table 8. Values used for M: input and prior medians

1. M value = 0.19
2. M vector = c(1.26,0.65,0.44,0.35,0.30,0.27,0.24,0.24)
3. M matrix (from the GAGDET model):

	1	2	3	4	5	6	7	8
1988	0.766	0.397	0.358	0.352	0.350	0.350	0.350	0.350
1989	1.125	0.842	0.388	0.356	0.351	0.350	0.350	0.350
1990	0.910	0.656	0.581	0.368	0.353	0.351	0.350	0.350
1991	0.455	0.410	0.367	0.361	0.351	0.350	0.350	0.350
1992	0.479	0.374	0.355	0.352	0.351	0.350	0.350	0.350
1993	0.406	0.389	0.355	0.351	0.350	0.350	0.350	0.350
1994	0.410	0.395	0.360	0.351	0.350	0.350	0.350	0.350
1995	0.471	0.419	0.357	0.351	0.350	0.350	0.350	0.350
1996	0.392	0.385	0.362	0.351	0.350	0.350	0.350	0.350
1997	0.373	0.362	0.358	0.353	0.350	0.350	0.350	0.350
1998	0.362	0.359	0.351	0.351	0.350	0.350	0.350	0.350
1999	0.367	0.363	0.353	0.350	0.350	0.350	0.350	0.350
2000	0.350	0.350	0.350	0.350	0.350	0.350	0.350	0.350
2001	0.350	0.350	0.350	0.350	0.350	0.350	0.350	0.350
2002	0.350	0.350	0.350	0.350	0.350	0.350	0.350	0.350
2003	0.350	0.350	0.350	0.350	0.350	0.350	0.350	0.350
2004	0.350	0.350	0.350	0.350	0.350	0.350	0.350	0.350
2005	0.350	0.350	0.350	0.350	0.350	0.350	0.350	0.350
2006	0.350	0.350	0.350	0.350	0.350	0.350	0.350	0.350
2007	0.350	0.350	0.350	0.350	0.350	0.350	0.350	0.350
2008	0.350	0.350	0.350	0.350	0.350	0.350	0.350	0.350
2009	0.350	0.350	0.350	0.350	0.350	0.350	0.350	0.350
2010	0.876	0.692	0.412	0.365	0.352	0.350	0.350	0.350
2011	0.822	0.683	0.457	0.370	0.354	0.351	0.350	0.350
2012	0.581	0.622	0.506	0.392	0.356	0.352	0.350	0.350
2013	0.592	0.656	0.497	0.403	0.363	0.353	0.351	0.350
2014	1.441	0.693	0.517	0.384	0.361	0.353	0.351	0.350
2015	1.425	0.894	0.480	0.415	0.364	0.356	0.352	0.350
2016	0.809	0.789	0.527	0.392	0.373	0.356	0.352	0.350

Table 9. Results of the posterior median over M for R32 and R37

Age	1	2	3	4	5	6	7	8
R32	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34
R37	1.17	0.57	0.36	0.26	0.27	0.34	0.30	0.38

Table 10. Settings of Bayesian SCAA runs. In the column labels *s1.Ccond* relates to interannual variability in selectivity and *s1.C* relates to CV of observation equation for catch at age; *cvf* and *cvrC* are prior CVs on f(y) and selectivity-at-age in initial year. Each row shows the settings that depart from those of "Base run"

Run	Base Run	*S1.Ccond*	Age groups survey catchability	Age groups CV of catch-at-age	Age groups CV of survey	Age groups interannual variabiltiy in selectivity	*S1.C*	*adep*	*cvf & cvrC*	M	Y/Y-1	Zeros	*medrec*	*cvrec*	*cvyear 1*	DIC	Penalty
1		4	All different	All different	All different	All different	4	1,2	1	0.19	Y-1	Incl	15000	2	1	1376	94.3
2	1	0.75	All different	All different	All different	All different	4	1,2	1	0.19	Y-1	Incl	15000	2	1	1128	329.5
3	2	0.75	1,2,3-6,7-8	All different	All different	All different	4	1,2	2	0.19	Y-1	Incl	15000	2	2	1010	206.5
4	2	0.75	1, 2-8	All different	All different	All different	4	1,2	1	0.19	Y-1	Incl	15000	2	1	1085	284.6
5	3	0.75	1,2,3-6,7-8	1-8	1-8	All different	4	1,2	2	0.19	Y-1	Incl	15000	2	2	1580	138.8
6	3	0.75	1,2,3-6,7-8	1-8	1-8	1-8	4	1,2	2	0.19	Y-1	Incl	15000	2	2	1646	98.9
7	3	0.75	1,2,3-6,7-8	1-2,3-6,7-8	All different	All different	4	1,2	2	0.19	Y-1	Incl	15000	2	2	1029	235.5
8	3	0.75	1,2,3-6,7-8	All different	All different	All different	100	1,2	2	0.19	Y-1	Incl	15000	2	2	511	222.7
9	2	0.75	1,2,3-8	All different	All different	All different	4	1,2	2	0.19	Y-1	Incl	15000	2	2	1000	221.1
10	9	0.75	1,2,3-8	All different	All different	All different	4	1	2	0.19	Y-1	Incl	15000	2	2	1092	269.4
11	10	0.75	1,2,3-8	All different	All different	1,2-8 (-5)	4	1	2	0.19	Y-1	Incl	15000	2	2	1037	189.7
12	11	0.75	1,2,3-8	1-2,3-6,7-8	All different	1,2-8 (-5)	4	1	2	0.19	Y-1	Incl	15000	2	2	1154	182.6
13	12	0.75	1,2,3-8	1-2,3-6,7-8	1,2,3-8	1,2-8 (-5)	4	1	2	0.19	Y-1	Incl	15000	2	2	1191	183.5
14	12	0.75	1,2,3-8	1-2,3-6,7-8	1,2-8	1,2-8 (-5)	4	1	2	0.19	Y-1	Incl	15000	2	2	1217	168.8
15	14	0.75	1,2,3-8	1-2,3-6,7-8	1,2-8	1,2-8 (-5)	4	1	4	0.19	Y-1	Incl	15000	4	4	1350	292.4
16	14	0.75	1,2,3-8	1-2,3-6,7-8	1,2-8	1,2-8 (-5)	4	1	16	0.19	Y-1	Incl	15000	16	16	1298	259.4
17	11	0.75	1,2,3-8	All different	All different	1,2-8 (-5)	4	1	2	0.19	Y	Incl	15000	2	2	1119	233.7
18	11	0.75	1,2,3-8	All different	All different	1,2-8 (-5)	4	1	4	0.19	Y-1	Incl	15000	4	4	1085	229.3
19	18	0.75	1,2,3-8	All different	All different	1,2-8 (-5)	4	1	4	0.19	Y	Incl	15000	4	2	1135	276.3
20	15	0.75	1,2,3-8	1-2,3-6,7-8	1,2-8	1,2-8 (-5)	4	1	4	0.19	Y	Incl	15000	4	4	1272	246.0
21*	19	0.75	1,2,3-8	All different	All different	1,2-8 (-5)	4	1	4	0.19	Y	Incl	15000	4	4	1449	176.0
22	19	0.75	1,2,3-8	All different	All different	1,2-8 (-5)	4	1	4	Vector	Y	Incl	15000	4	4	1108	269.8
23	19	0.75	1,2,3-8	All different	All different	1,2-8 (-5)	4	1	4	Matrix	Y	Incl	15000	4	4	1052	194.4
24	19	0.75	1,2,3-8	All different	All different	1,2-8 (-5)	4	1	2,2	0.19	Y	Incl	15000	4	2	1131	250.7
25	19	0.75	1,2,3-8	All different	All different	1,2-8 (-5)	4	1	2,2	0.19	Y	Incl	15000	4	4	1072	204.8
26	19	0.75	1,2,3-8	All different	All different	1,2-8 (-5)	4	1	4,2	0.19	Y	Incl	15000	4	4	1157	276.5
27	19	0.75	1,2,3-8	All different	All different	1,2-8 (-5)	4	1	4,4	0.19	Y	Incl	15000	4	4	1913	896.1
28	19	NA	1,2,3-8	Fix (20%)	Fix (30%)	Fix (20%)	NA	1	4	1 prior	Y	Incl	15000	4	4	10501	170.1
29	28	NA	1,2,3-8	Fix (20%)	Fix (30%)	Fix (20%)	NA	1	4	0.19	Y	Incl	15000	4	4	10481	125.8
30	19	0.75	1,2,3-8	All different	All different	1,2-8 (-5)	4	1	4	1 prior	Y	Incl	15000	4	4	994	219.3
31	19	0.75	1,2,3-8	All different	All different	1,2-8 (-5)	4	1	4	8 priors	Y	Incl	15000	4	4	1022	229.3
32	28	NA	1,2,3-8	Fix (20%)	Fix (30%)	Fix (20%)	NA	1	4	1 prior	Y	NA	15000	4	4	1612	127.0
33	32	NA	1,2,3-8	Fix (20%)	Fix (30%)	Fix (20%)	NA	1	4	8 priors	Y	NA	15000	4	4	1639	148.8
34	28	NA	1,2,3-8	Fix (20%)	Fix (30%)	Fix (20%)	NA	1	4	8 priors	Y	Incl	15000	4	4	9736	130.1
35	34	NA	1,2,3-8	Fix (20%)	Fix (30%)	Fix (20%)	NA	1	4	8 priors, medM	Y	Incl	15000	4	4	9693	128.4
36	34	NA	1,2,3-8	Fix (20%)	Fix (30%)	Fix (20%)	NA	1	4	8 priors, cvM	Y	Incl	15000	4	4	9693	161.8
37	33	NA	1,2,3,4-8	Fix (20%)	Fix (30%)	Fix (20%)	NA	1	4	8 priors, cvM=0.15	Y	NA	15000	4	4	1596	121.7
38	37	NA	1,2,3,4-8	Fix (30%)	Fix (20%)	Fix (30%)	NA	1	4	8 priors, cvM=0.15	Y	NA	15000	4	4	2142	142.2
39	37	NA	1,2,3,4-8	Fix (20%)	Fix (30%)	Fix (20%)	NA	1	4	8 priors, cvM=0.15	Y	NA	45000	4	4	1656	158.3
40	37	NA	1,2,3,4-8	Fix (20%)	Fix (30%)	Fix (20%)	NA	1	4	8 priors, cvM=0.15	Y	NA	15000	10	4	1524	100.3
41	40	NA	1,2,3,4-8	Fix (20%)	Fix (30%)	Fix (20%)	NA	1	4	8 priors, cvM=0.15	Y	NA	45000	10	4	1581	128.6
42	37	NA	1,2,3,4-8	Fix (20%)	Fix (30%)	Fix (20%)	NA	1	4	8 priors, cvM=0.15	Y	NA	45000	10	10	1579	123.1
43**	42	NA	1,2,3,4-8	Fix (20%)	Fix (30%)	Fix (20%)	NA	1	4	8 priors, cvM=0.15	Y	NA	45000	10	10	1588	116.5
44	37	NA	1,2,3,4-8	Fix (20%)	Fix (30%)	Fix (20%)	NA	1	4	0.19	Y	NA	15000	4	4	1694	139.8

R21*: We do not use the total catch tons except for the years without caa

R35: *medM*=c(0.19,0.19,0.19,0.19,0.19,0.19,0.19,0.19); R36: *cvM*=1 ; R43**: As R42 but *medF*=c(0.001,0.1,0.5,0.7,0.35,0.35,0.35)

Table 11. Median SSB (million tons) for the different runs of the Bayesian SCAA.

Year	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12	R13	R14	R15	R16	R17	R18	R19	R20	R21	R22	R23	R24	R25	R26	R27	R28	R29	R30	R31	R32	R33	R34	R35	R36	R37	R38	R39	R40	R41	R42	R43	R44
1988	23	23	24	20	25	25	23	20	20	20	21	20	20	20	18	18	21	21	21	19	18	24	25	21	21	21	20	28	17	28	24	24	23	23	21	21	23	21	24	23	24	23	24	19
1989	31	31	32	28	32	33	32	28	28	28	29	29	28	28	27	26	29	28	28	27	28	32	35	28	29	29	27	35	23	37	32	30	29	28	27	26	30	29	30	29	30	30	30	26
1990	33	32	32	28	34	36	32	28	29	28	30	31	29	29	28	27	30	29	29	28	33	32	35	29	29	29	30	37	25	37	33	33	32	31	30	30	33	32	33	32	33	33	33	29
1991	27	23	23	20	28	30	24	20	20	19	23	24	22	22	20	19	23	21	21	21	21	24	25	21	21	21	23	27	18	27	24	25	25	24	22	24	25	23	25	25	25	25	25	20
1992	34	29	28	22	36	39	31	24	23	22	30	32	26	25	23	22	30	28	27	24	20	28	30	28	28	28	28	26	19	31	27	26	25	26	25	26	25	21	26	25	26	26	26	23
1993	12	13	12	9	14	15	13	11	10	9	10	10	10	10	9	9	10	9	10	9	8	10	11	9	9	9	8	12	8	12	11	11	10	11	11	10	10	9	11	10	10	10	10	9
1994	20	18	18	16	23	25	17	19	16	16	18	19	18	18	18	17	18	18	18	18	16	19	20	18	18	18	17	22	15	21	20	22	21	19	19	18	21	19	22	21	21	21	22	19
1995	12	14	14	13	12	11	14	13	13	13	13	13	13	13	12	12	13	13	13	12	13	14	15	13	13	13	11	15	11	16	14	14	14	12	12	12	13	13	14	14	14	14	14	12
1996	4	4	4	3	3	4	4	3	3	3	4	4	3	3	3	3	4	3	3	3	4	4	4	3	3	3	3	4	3	5	4	4	4	3	3	3	4	4	4	4	4	4	4	3
1997	5	5	4	3	4	5	5	2	4	3	4	5	3	3	3	3	4	4	4	3	5	4	5	4	4	4	4	4	2	6	5	4	4	3	3	3	4	4	4	4	4	4	4	3
1998	5	6	5	3	5	5	6	1	4	3	5	6	2	2	2	2	4	4	4	2	3	4	6	4	4	4	3	4	1	7	5	3	3	4	3	4	3	3	3	3	3	3	3	2
1999	5	6	5	3	6	6	6	0	4	3	5	7	2	2	1	1	4	3	3	1	3	3	5	3	3	4	3	3	1	6	5	2	2	3	3	4	2	2	2	2	2	2	2	1
2000	6	7	6	3	7	7	8	0	5	4	6	8	2	2	1	1	5	4	4	1	2	4	5	4	4	4	3	2	0	6	5	2	2	3	3	4	2	2	2	2	2	2	2	1
2001	5	7	6	4	7	7	7	0	5	4	6	8	2	2	1	1	6	4	4	2	2	4	5	4	4	4	3	2	0	5	5	2	2	3	3	3	2	2	2	2	2	2	2	1
2002	6	7	7	4	8	8	8	0	5	4	6	8	3	3	2	1	6	5	5	2	3	4	5	5	5	5	4	4	1	5	4	2	2	4	4	4	2	2	2	2	2	2	2	2
2003	6	8	8	4	9	9	9	0	6	5	7	9	4	3	2	2	6	5	5	2	3	4	5	5	5	5	4	5	1	5	4	3	3	3	3	3	3	2	3	3	3	3	3	2
2004	8	10	10	6	12	13	11	1	8	7	9	11	5	5	3	3	8	7	7	4	4	6	6	7	7	7	6	7	2	7	5	5	4	5	5	5	4	4	4	4	4	4	4	3
2005	9	11	11	7	14	15	12	3	9	8	9	11	7	6	4	4	9	8	7	5	5	7	7	8	7	8	6	9	3	8	6	7	6	7	6	7	6	5	7	6	7	7	7	5
2006	13	15	15	10	21	22	16	7	13	11	13	15	10	10	7	6	13	11	11	8	8	10	11	11	11	11	9	14	5	11	9	11	10	12	11	12	10	9	11	10	11	11	11	8
2007	16	18	19	13	27	28	20	10	15	14	16	18	14	14	10	9	15	13	13	11	11	13	15	13	13	13	12	19	8	16	13	16	15	17	16	17	15	12	15	15	15	15	15	11
2008	27	27	28	20	42	44	30	17	23	22	25	28	23	23	17	16	24	21	21	19	19	23	28	21	21	21	20	36	14	31	25	28	26	27	25	26	26	23	26	26	26	26	26	19
2009	45	44	46	33	66	68	49	27	37	35	39	45	37	37	29	27	38	35	34	31	32	36	45	34	34	34	34	53	23	50	41	44	41	40	38	37	41	39	41	41	41	41	41	31
2010	67	66	68	51	93	95	73	39	56	53	58	65	54	54	43	41	57	52	51	47	50	53	65	51	51	51	51	72	35	70	61	62	59	60	57	61	59	56	60	59	60	60	60	47
2011	64	64	65	48	91	92	70	34	52	50	55	62	51	51	39	37	53	49	47	43	46	46	57	48	48	48	48	58	30	60	54	54	52	52	50	52	52	48	53	52	53	53	52	43
2012	69	70	72	51	101	101	76	31	56	54	61	68	55	55	41	38	58	53	51	45	51	48	60	52	51	52	51	59	29	64	58	57	55	56	55	57	55	49	56	55	56	56	56	45
2013	99	100	103	74	148	148	109	43	82	78	92	103	88	85	64	59	90	81	79	71	73	78	94	79	78	79	73	97	43	101	87	95	90	83	79	80	90	82	92	91	91	92	92	72
2014	108	110	113	79	165	164	121	40	88	84	100	113	97	92	67	61	97	87	84	76	78	75	87	86	84	85	77	84	41	94	83	92	89	80	78	81	89	82	91	90	90	90	90	76
2015	98	102	106	75	157	157	112	35	84	79	96	107	95	90	64	59	93	83	81	73	71	67	75	82	80	82	71	71	37	81	73	86	84	73	72	76	84	78	86	85	85	86	85	76
2016	111	117	121	85	179	183	127	36	98	92	112	125	112	104	73	66	108	96	95	84	84	72	76	95	93	95	80	68	38	83	77	93	93	78	80	84	93	87	95	94	95	95	94	90

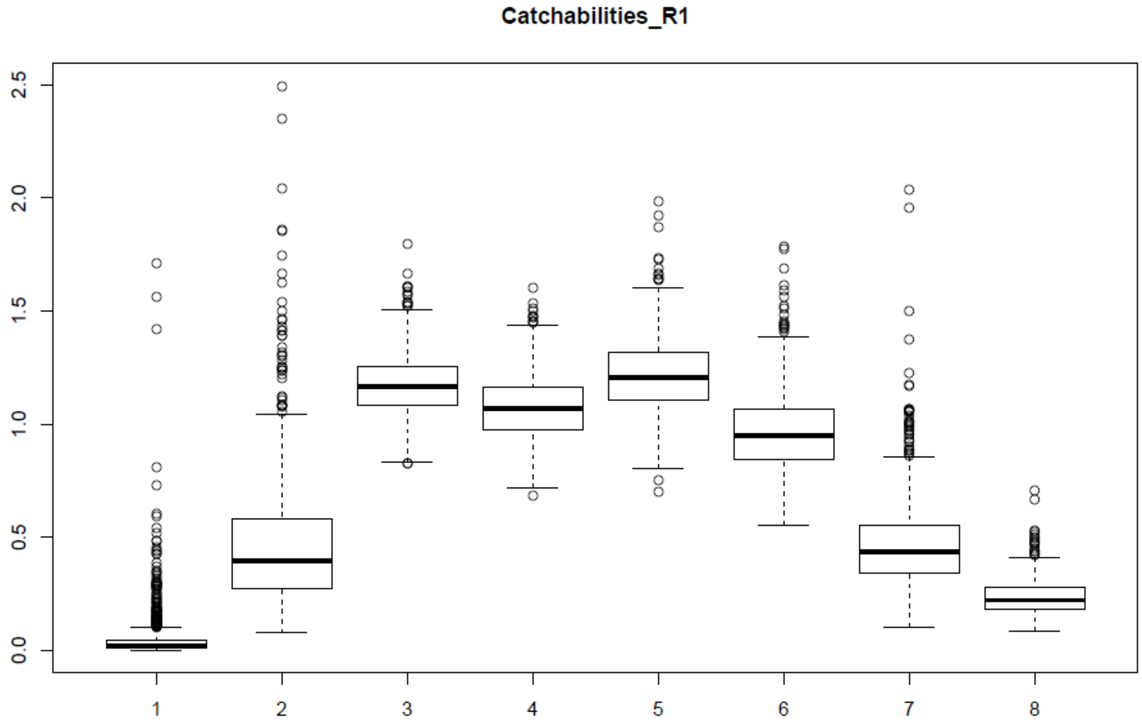

Fig. 1. Posterior catchability in R1

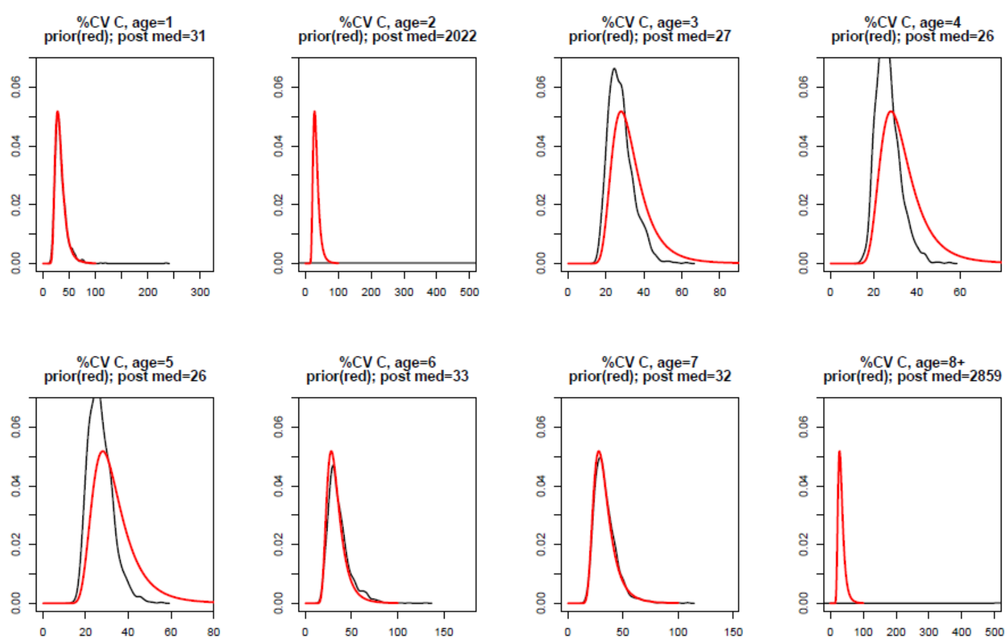

Fig. 2. Prior and posterior of the CV of the catch-at-age in R19

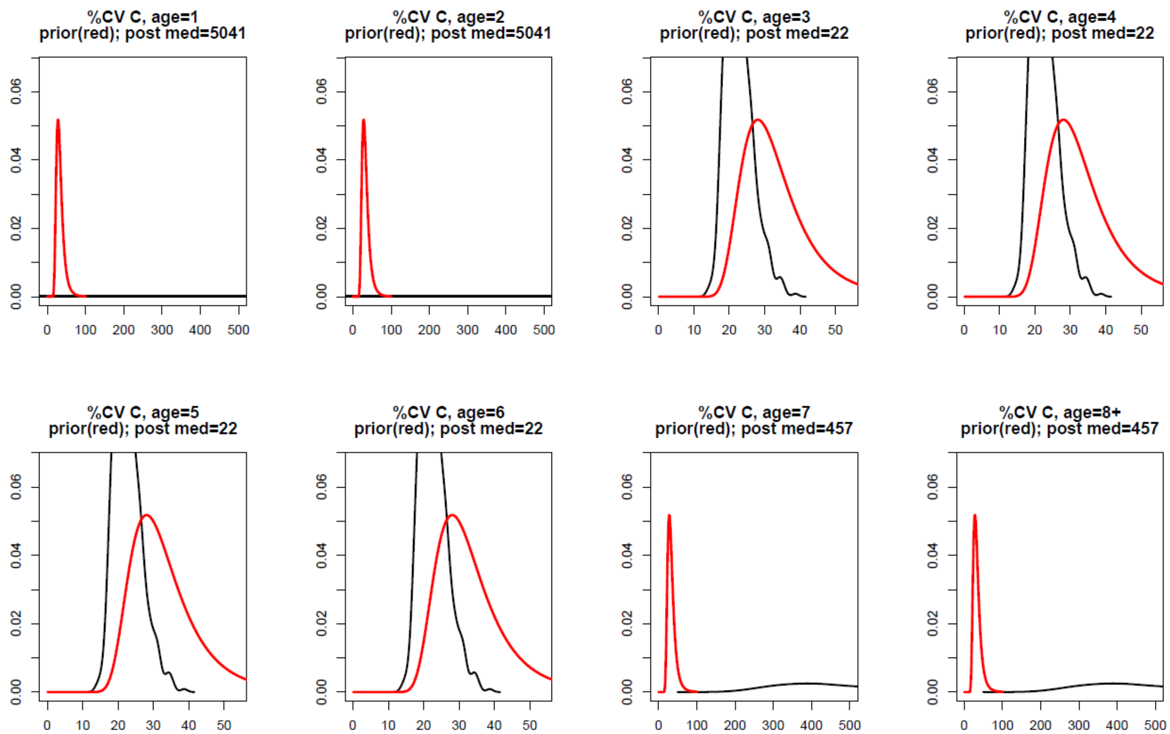

Fig. 3. Prior and posterior of the CV of the catch-at-age in R20

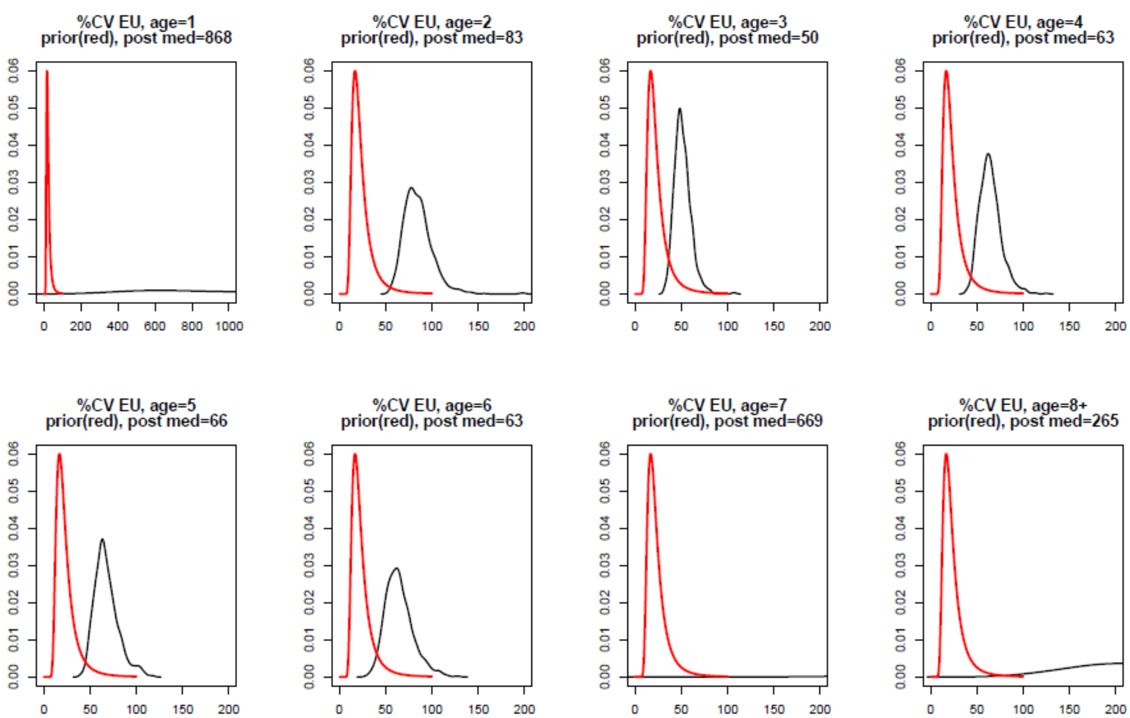

Fig. 4. Prior and posterior of the CV of the abundance EU survey index in R19

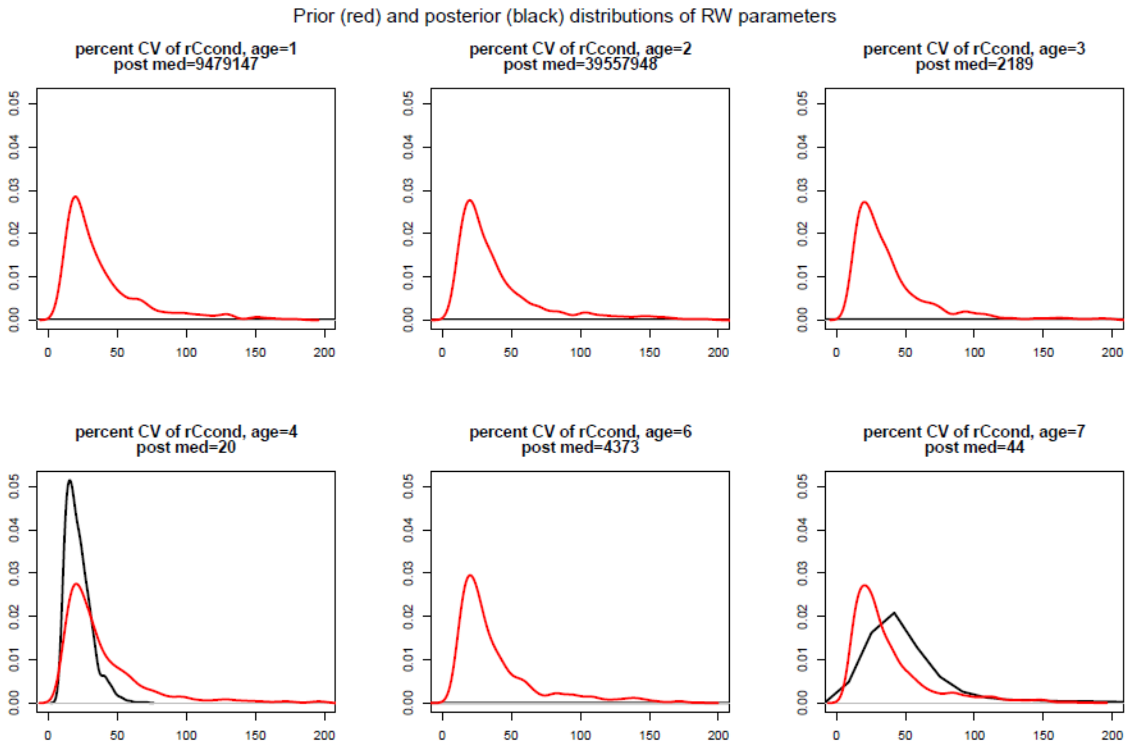

Fig. 5. Prior and posterior of the variability of the selectivity at age over the years in R10

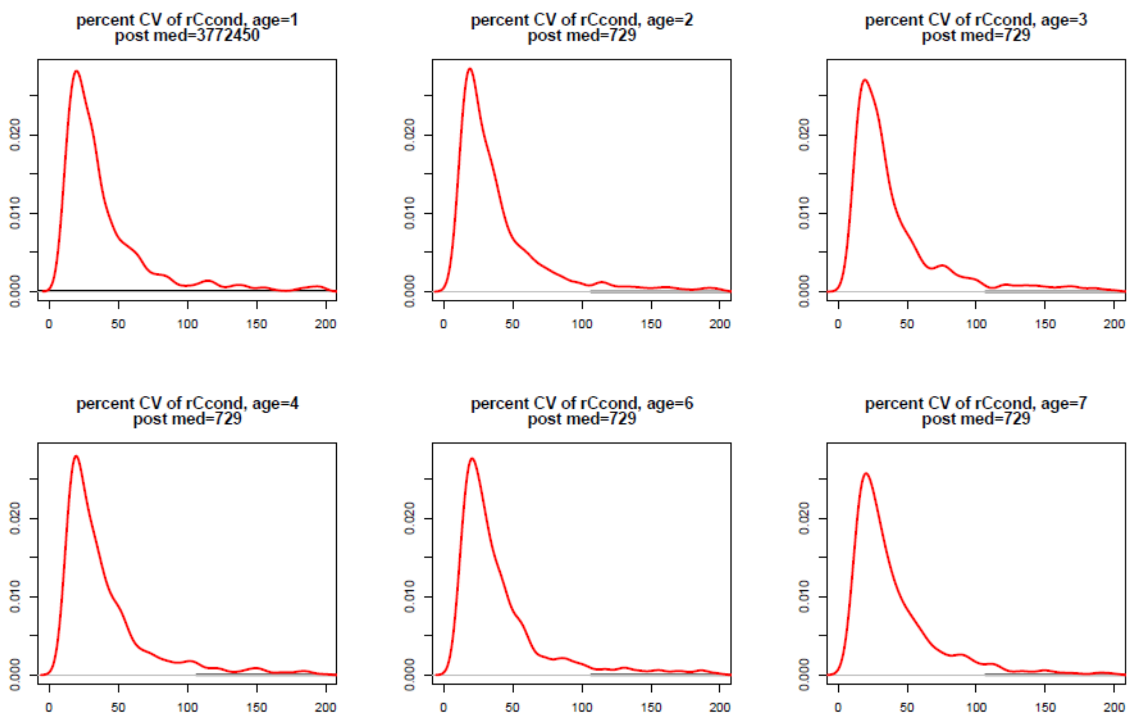

Fig. 6. Prior and posterior of the variability of the selectivity at age over the years in R19

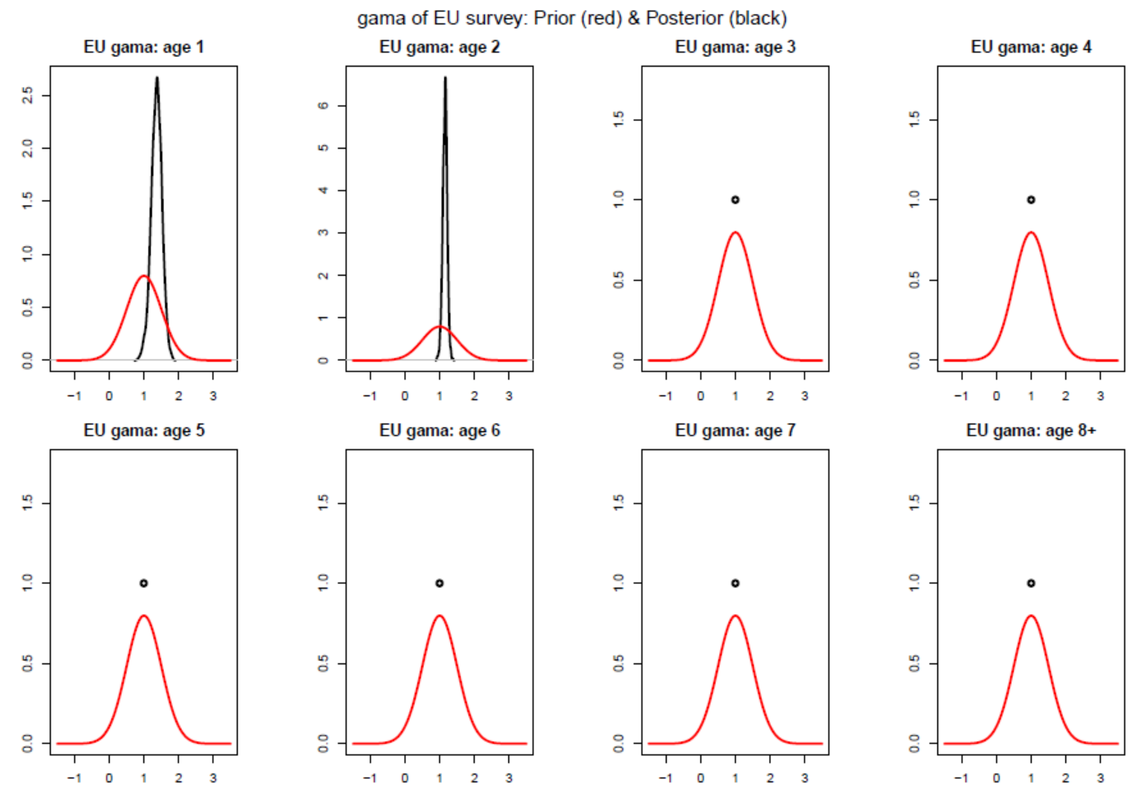

Fig.7. Prior and posterior of the gama.EU parameter in R9

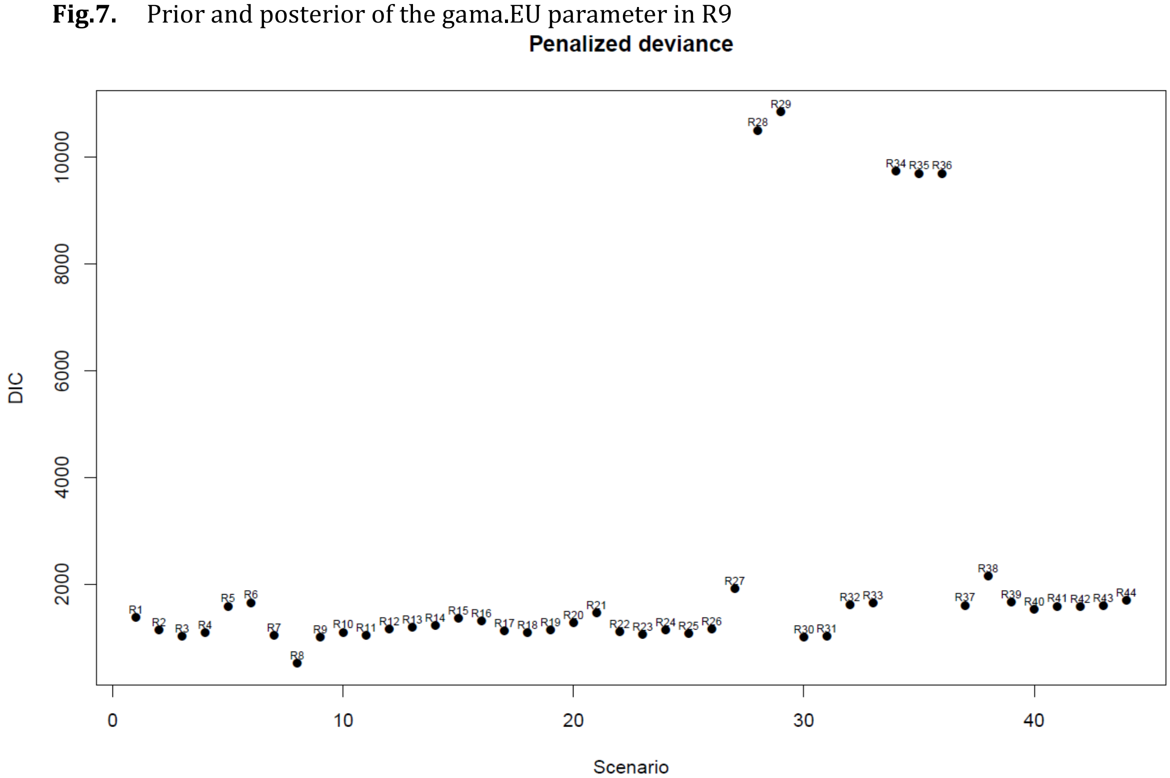

Fig. 8. DIC values for the Bayesian SCAA: R1-R44.

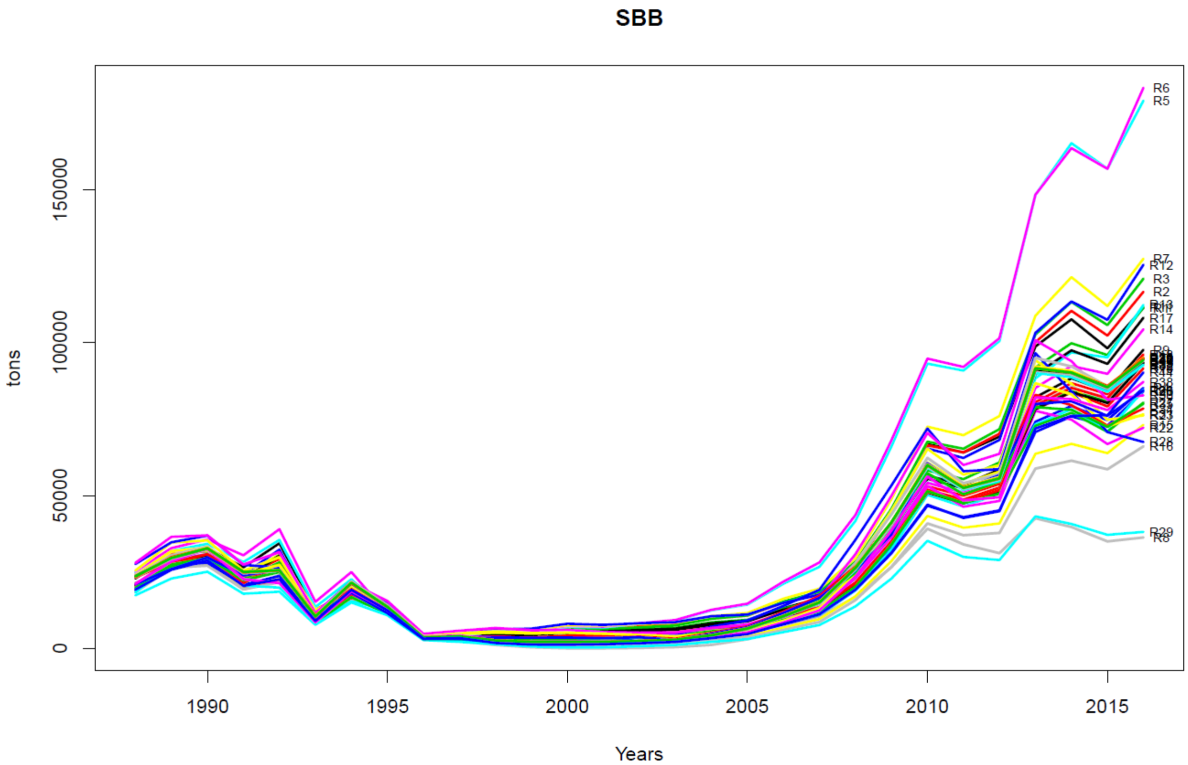

Fig. 9. Results of the median SSB for the different runs of the Bayesian SCAA (R1-R44).

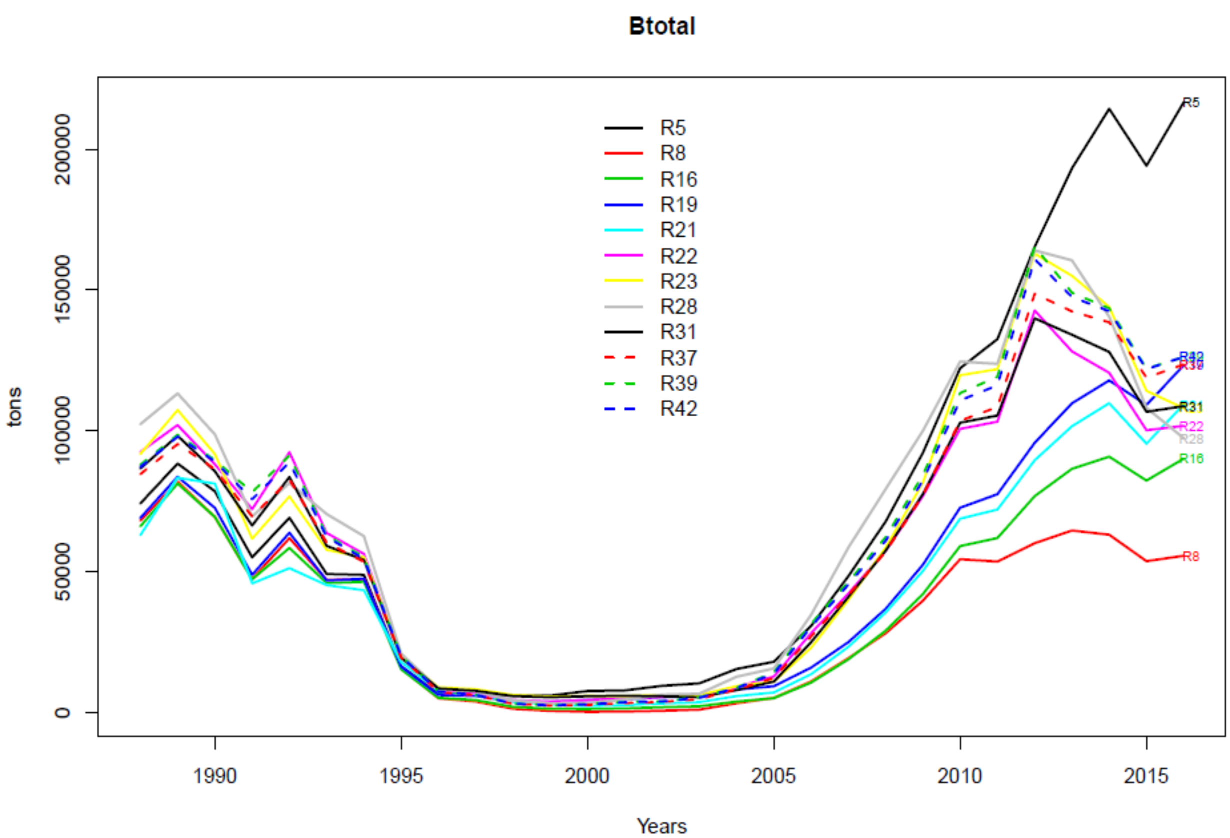

Fig. 10. Median total Biomass for selected Bayesian SCAA scenarios.

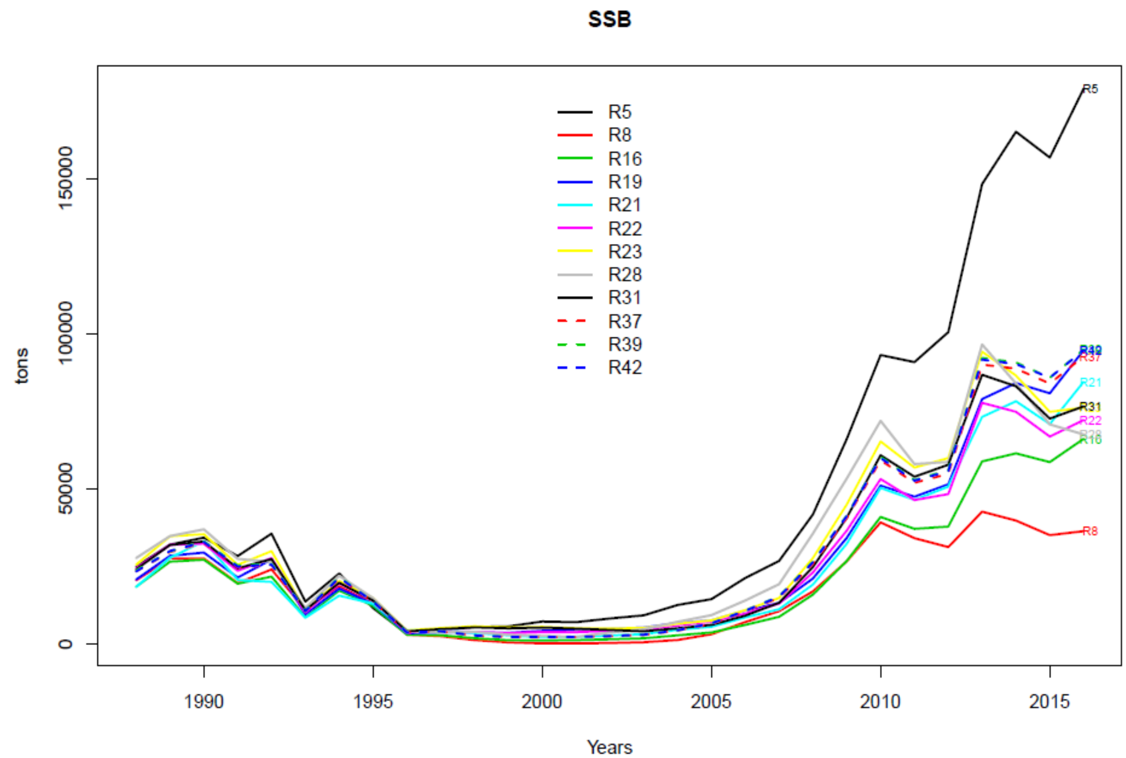

Fig. 11. Median SSB for selected Bayesian SCAA scenarios.

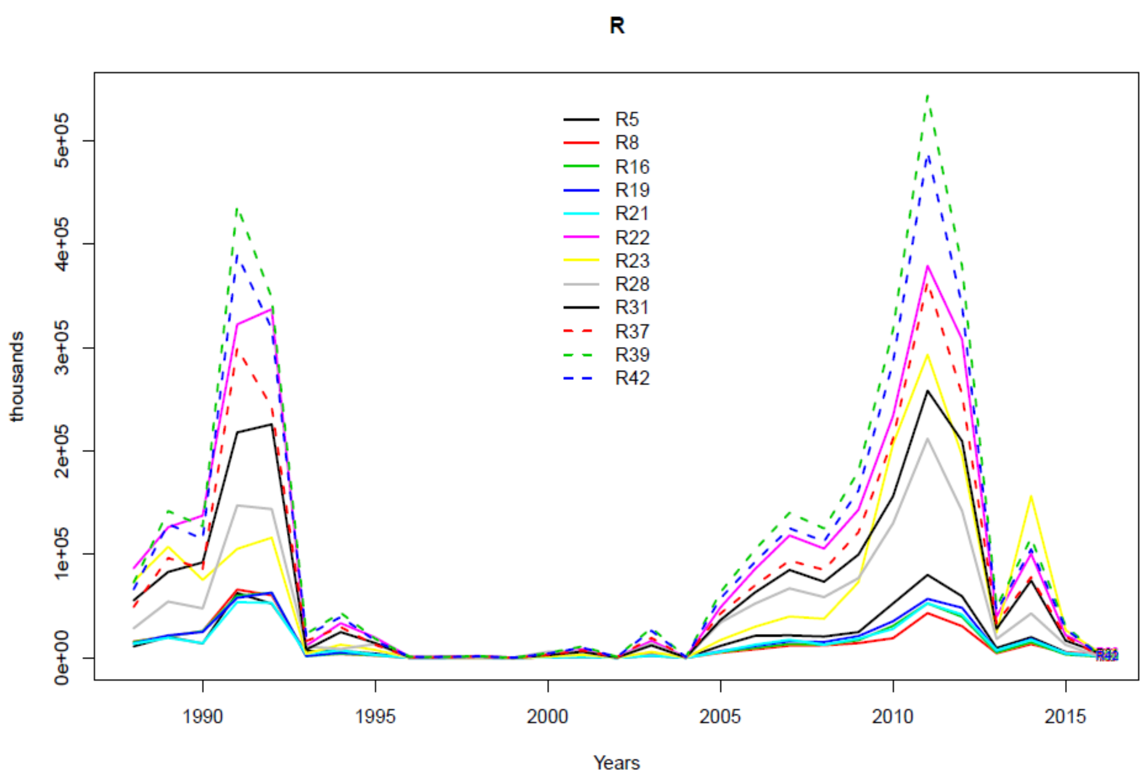

Fig. 12. Median recruitment for selected Bayesian SCAA scenarios.

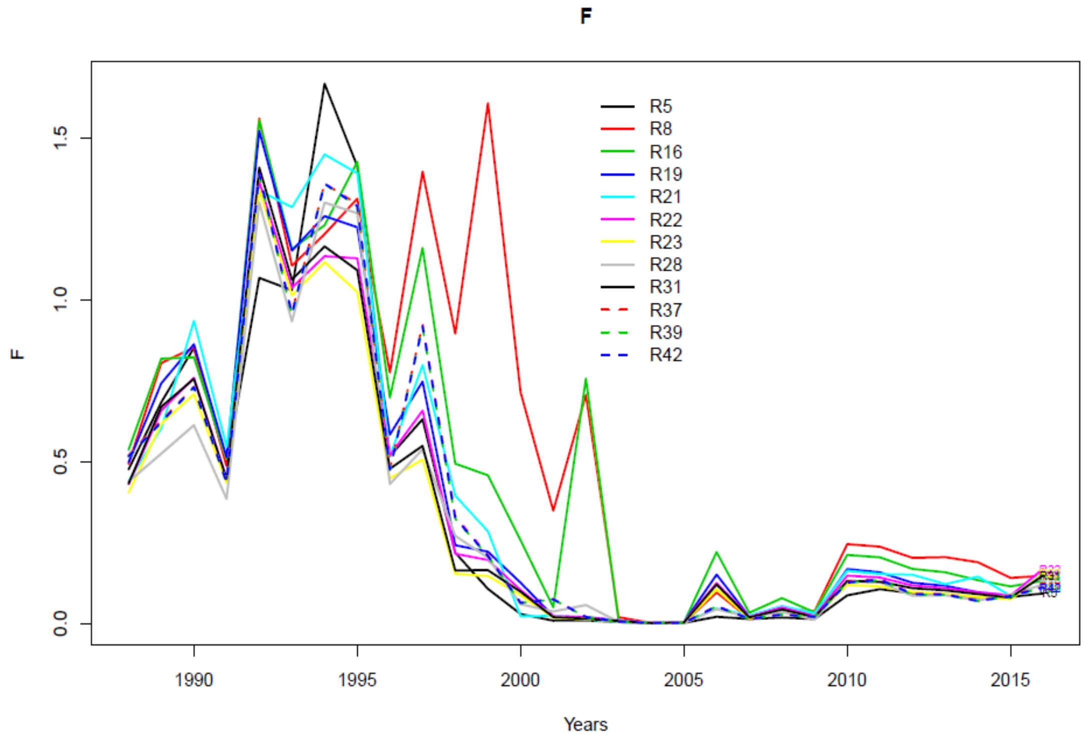

Fig.13. Median Fbar(3-5) for selected Bayesian SCAA scenarios.

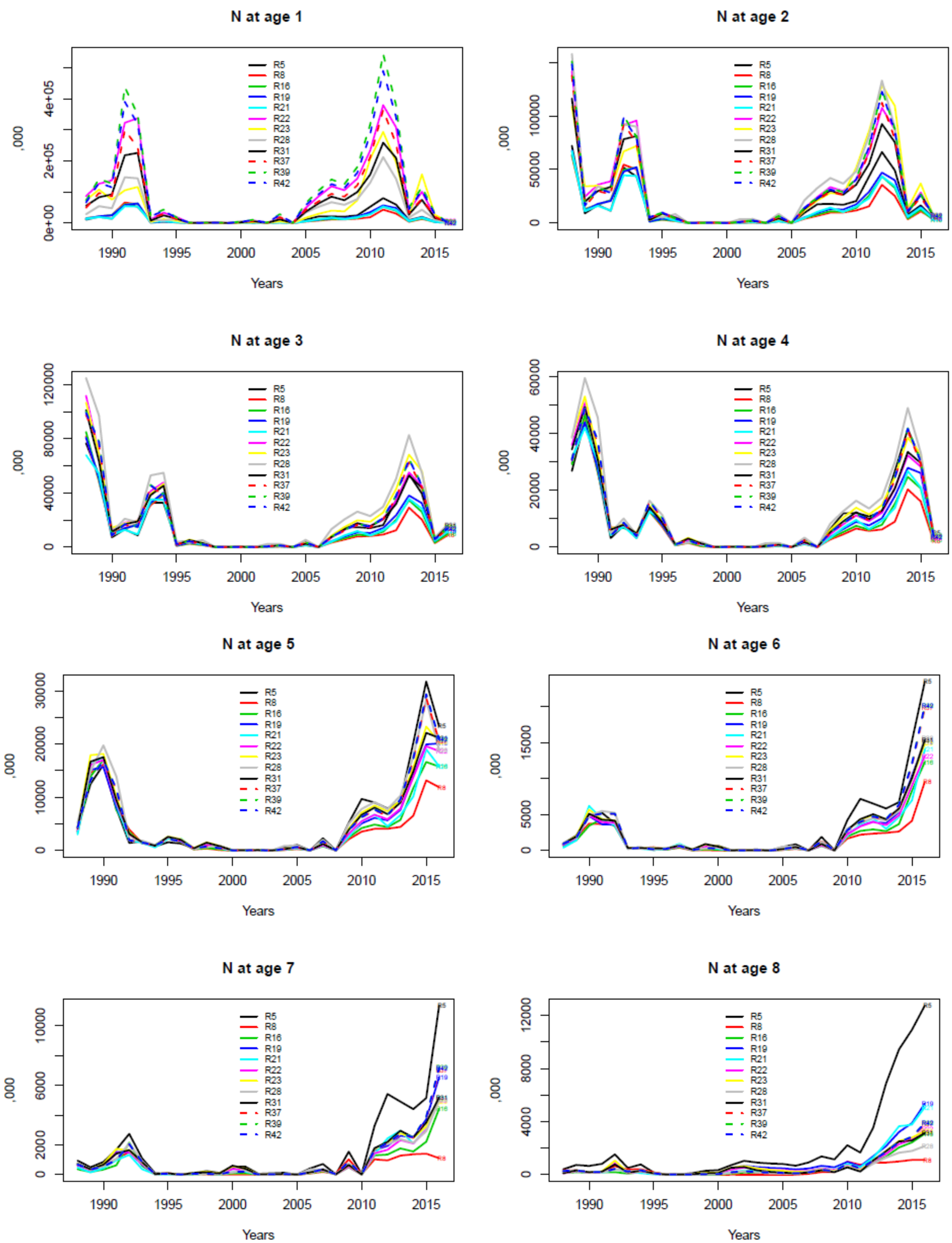

Fig. 14. Median N at age for selected Bayesian SCAA scenarios.

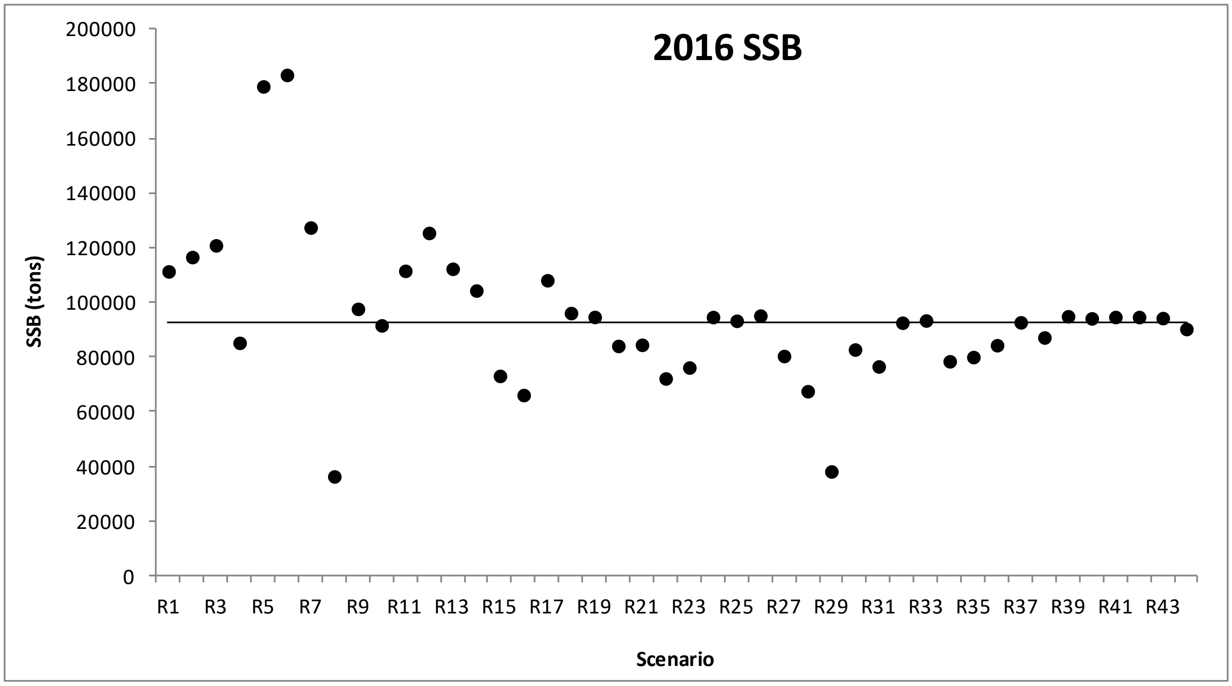

Fig. 15. Median SSB in 2016 for R1-R44. The horizontal line is the SSB in 2016 of R37.

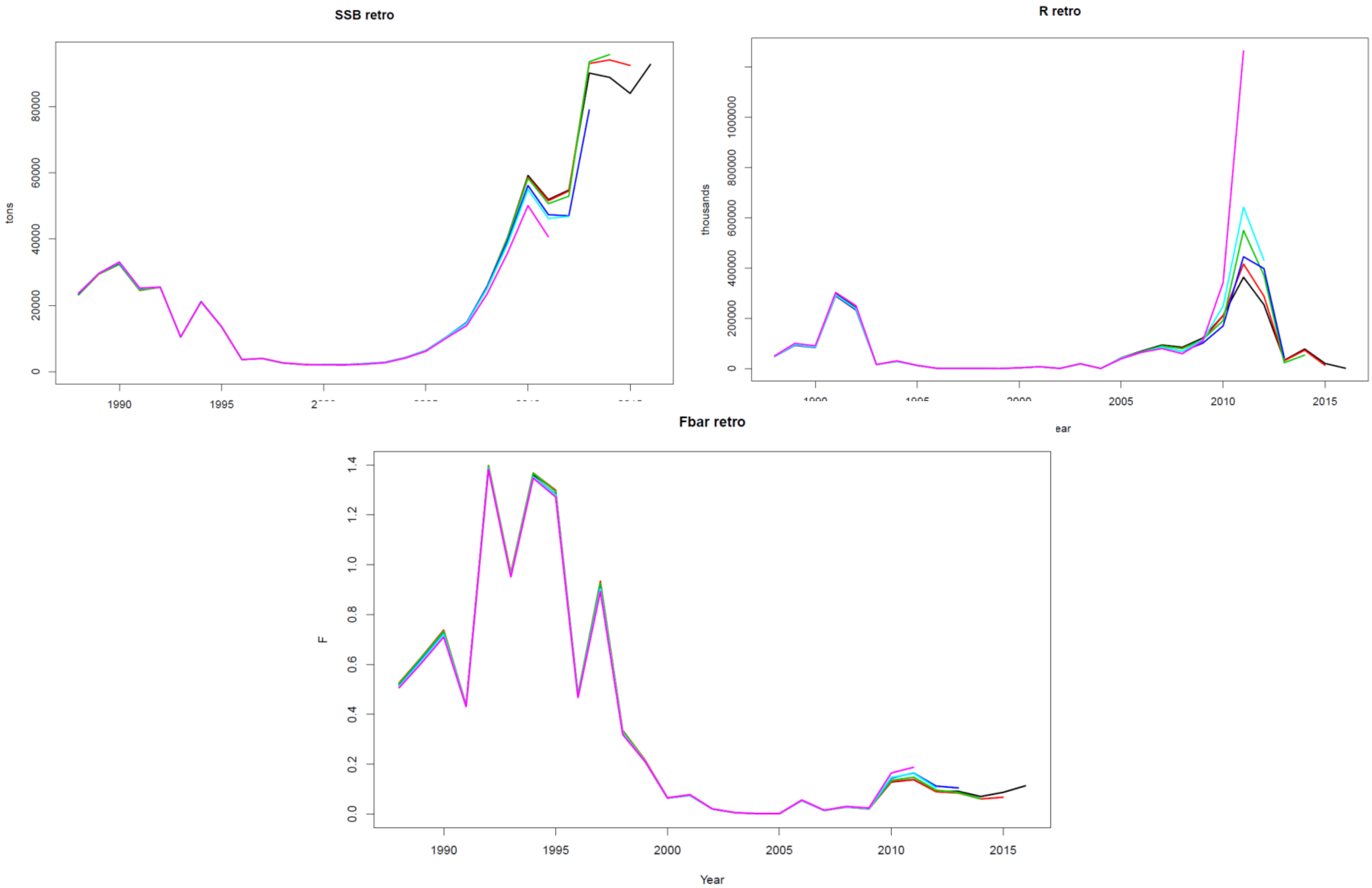

Fig. 16. Retrospective pattern (5 years) for R37

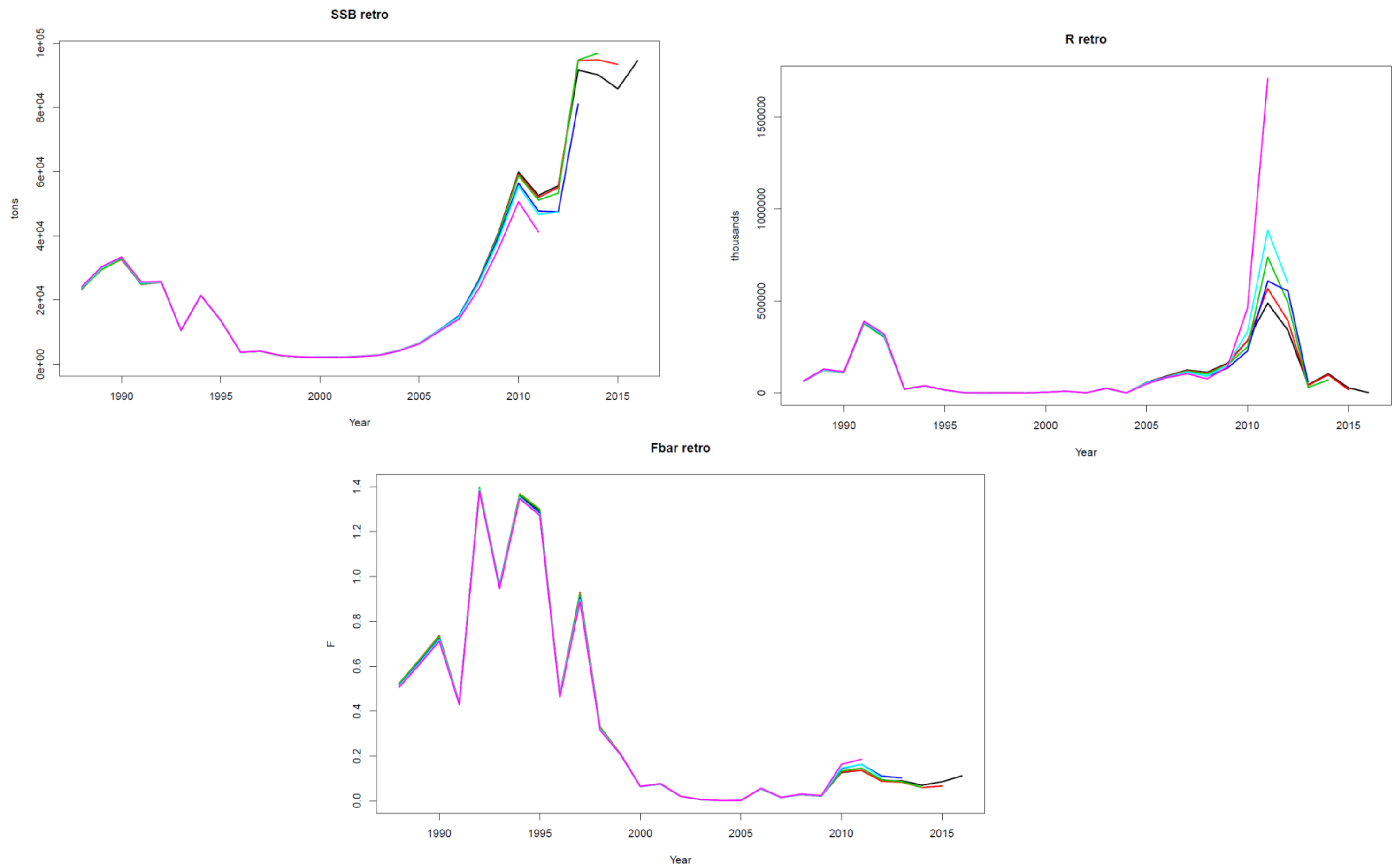

Fig. 17. Retrospective pattern (5 years) for R42

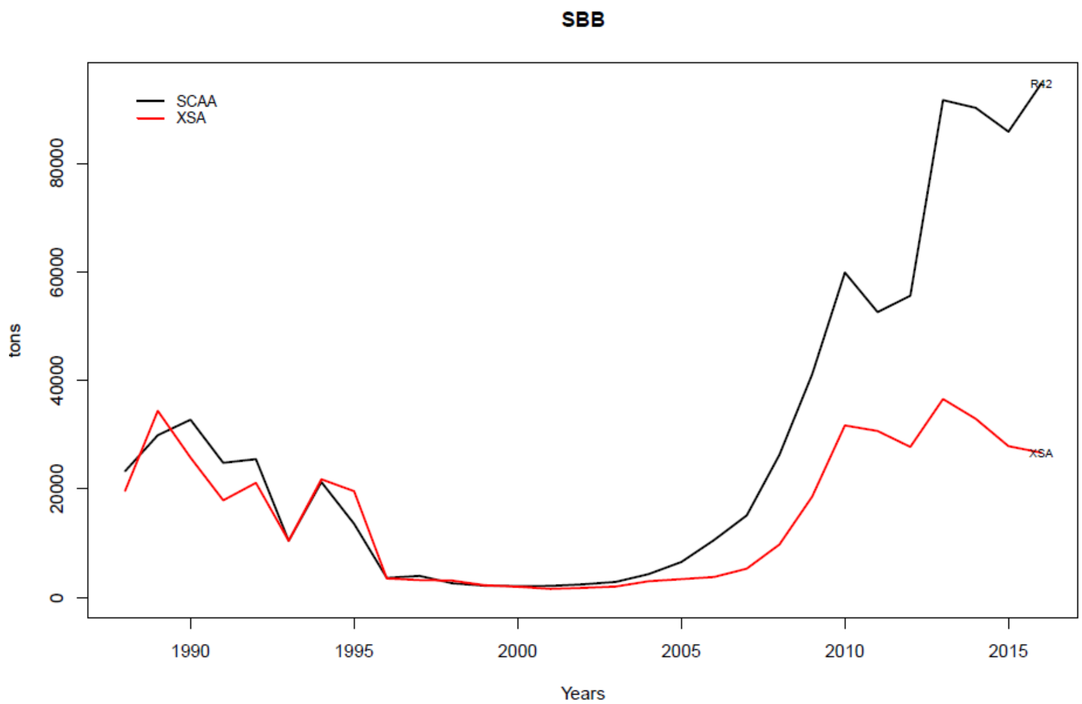

Fig. 18. SSB comparison between R42 Bayesian SCAA and approved assessment (common years).

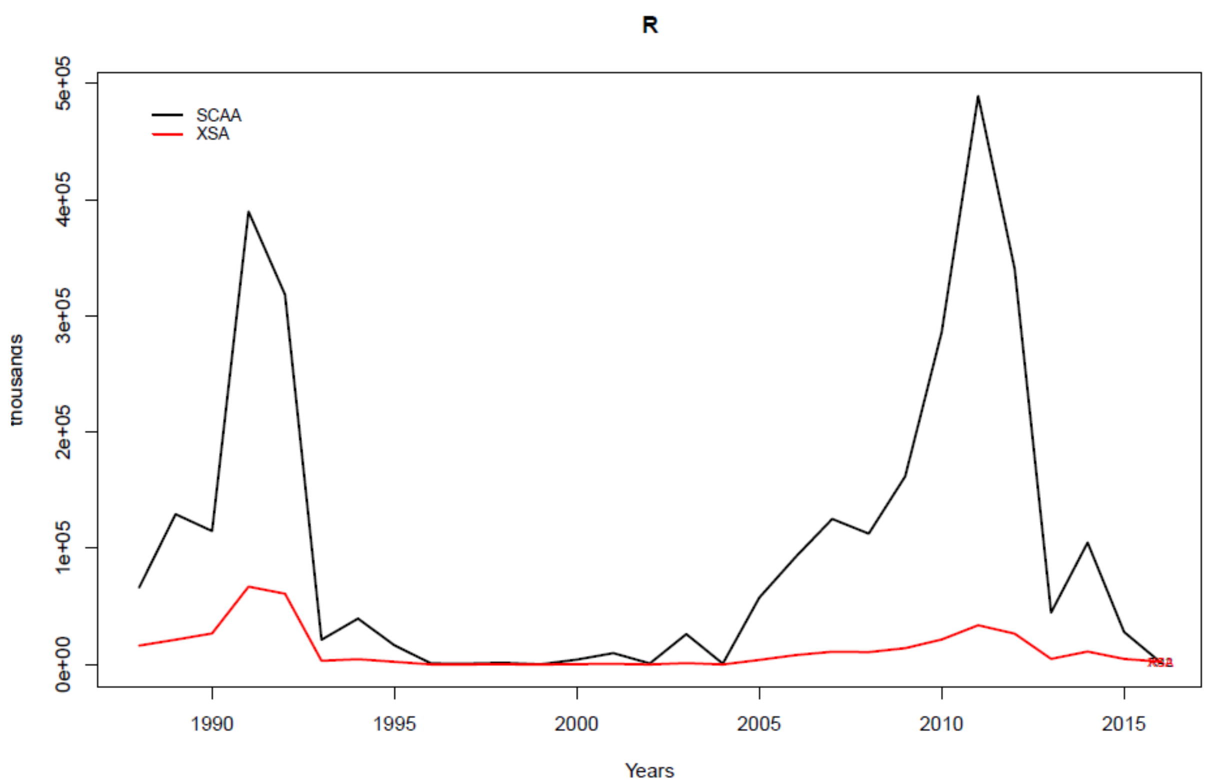

Fig.19. R comparison between R42 Bayesian SCAA and approved assessment (common years).

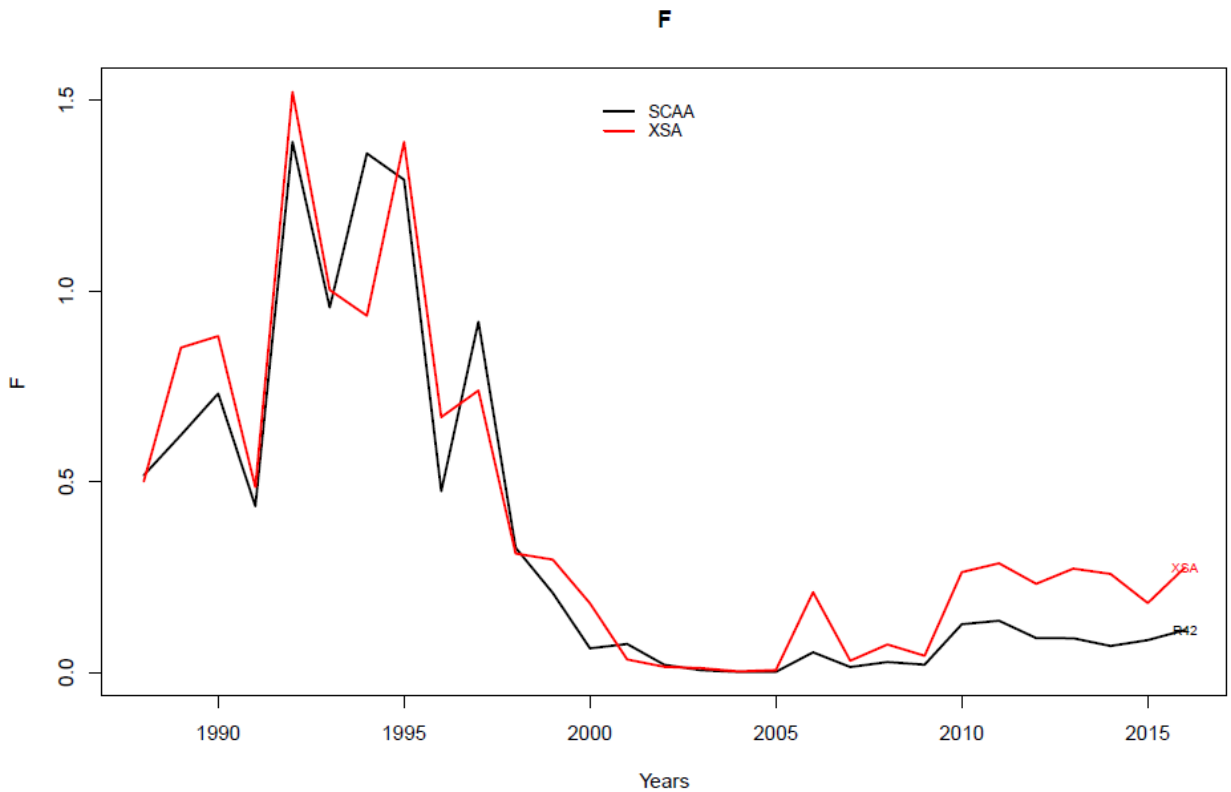

Fig. 20. F_{bar}(3-5) comparison between R42 Bayesian SCAA and approved assessment (common years).

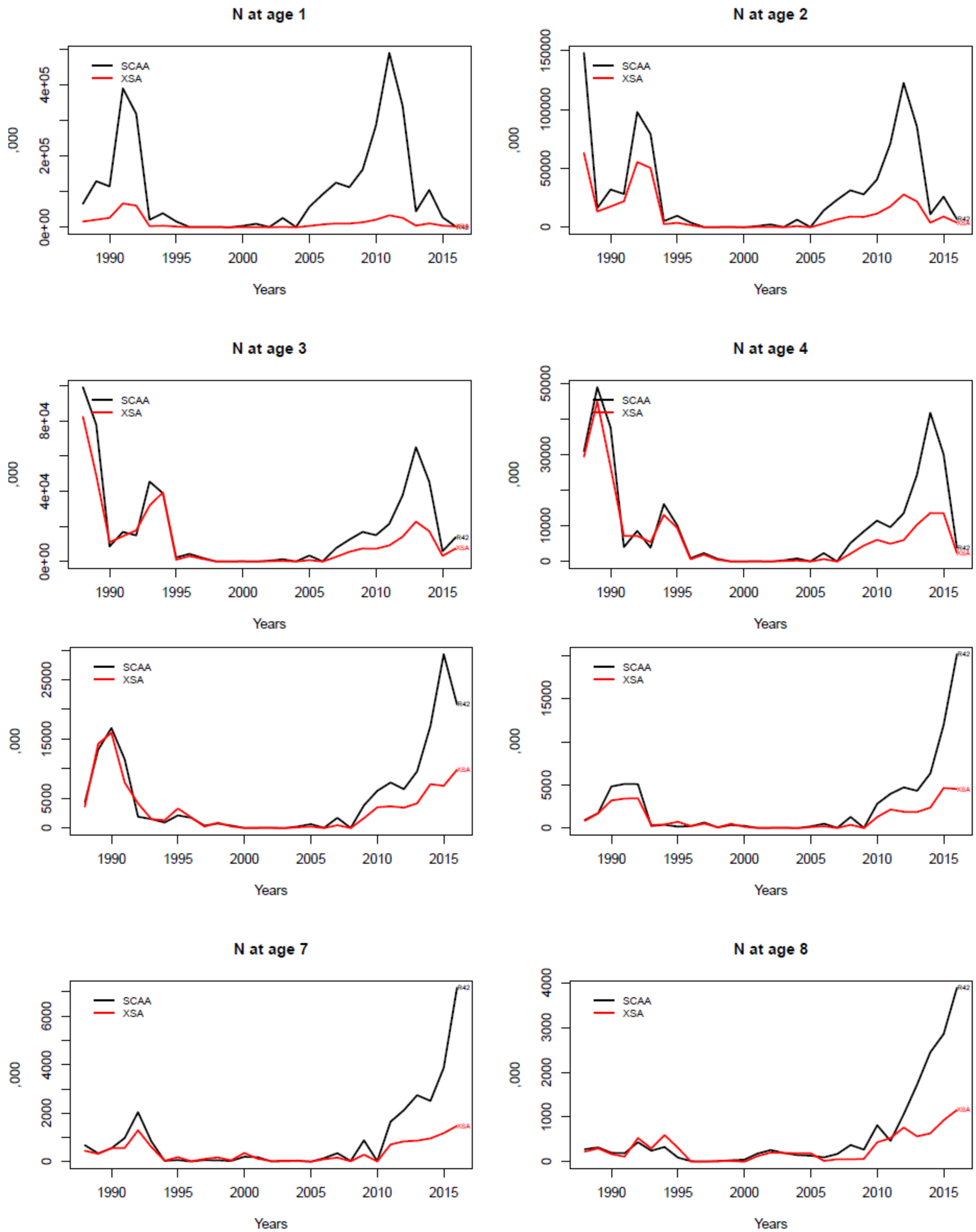

Fig. 21. N comparison between R42 Bayesian SCAA and approved assessment (common years).

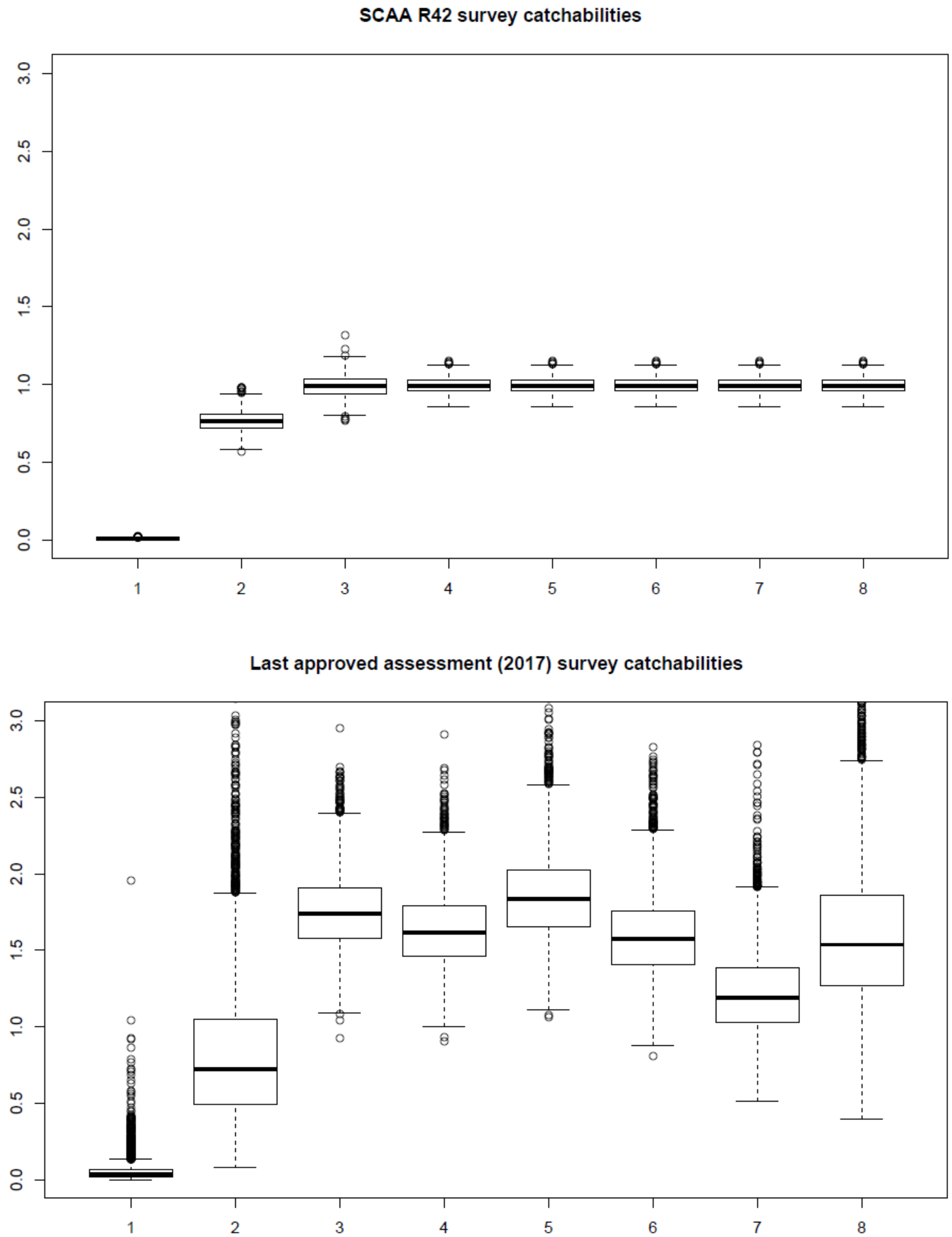

Fig. 22. Survey catchabilities for SCAA R42 (up) and for the XSA last approved assessment in 2017 (down). The XSA estimates the catchabilities to be different for all ages (1-8+), while the SCAA groups the ages (1, 2, 3 and 4-8+). The y-axis of both plots are set to be the same.